TOWARDS MITIGATING ENGINE-OUT EMISSIONS: A MIGRATION TO FUEL BASED AND COMBUSTION BASED SOLUTIONS

Rasheed Adewale Opatola, A. Rashid A. Aziz, Morgan Raymond Heikal and Mior Azman Meor Said
Centre for Automotive Research and Energy Management, University Teknologi Petronas, Bandar Seri Iskandar, Perak, Malaysia
E-Mail: surulere_opatola@hotmail.com

ABSTRACT

Road transport is a key source of ambient pollution especially in urban regions. While the moderation of engine-out emissions from road transport is seen as key in the improvement of global air quality, the overall sales of automobiles which contribute to air pollution keep rising. This trend has impelled global alertness due to the grave consequences of human exposure to air pollutants. In this light, a study was conducted to review the steps that are being taken by stakeholders in the automotive industry in contending the menace, in terms of research and development; the economy cum the suitability of the methods and devices that are being used in extenuating engine-out emissions. The study revealed that modern hardware based solutions such as high-pressure fuel injection equipment (FIE), sophisticated piezo-injectors, diesel particulate filters (DPF) and associated control systems are prevalent among the existing methods in use by engine designers and manufacturers. However, these technologies are prone to salient setbacks such as limited durability, high cost and difficulty in installing on extant engines, among others. Hence, much as the modern hardware based solutions had to offer, yet there were no one-size-fits-all solutions in place. Most of the existing solutions enjoy, at best, relative advantages over one another. Conversely, the significant revelation of this study were the plethora of prospects that the fuel based solutions and combustion based solutions could offer various stakeholders in the drive towards finding an enduring panacea to engine-out emissions. Therefore, there are room for progress in research and development toward finding sustainable solutions to the threats that engine-out emissions pose to humans and the environments.

Keywords: ambient pollutants, health hazards, natural gas, diesel, particulate, catalytic, EGR.

INTRODUCTION

The rising tide of human deaths due to ambient pollutants which globally stands at 2.7 million, with approximately 33% occurring in cities [1] is a source of concern to stakeholders. In China alone, over 400,000 premature deaths are attributed to air pollutants every year [2]. Engine-out emissions from automobiles form an integral part of these pollutants, particularly oxides of nitrogen (NO_x), particulate matter (PM), unburnt hydrocarbon (HC) and carbon monoxide (CO). Responsively, European Union had instituted rigorous criteria to regulate emissions for automobiles vended in European regions [3]. Accordingly, automotive engineers have intensified efforts towards ensuring that vehicular emissions become cleaner with particular focus on Diesel engines. These efforts have strengthened research and development targeted at reducing automobile emissions, especially NO_x and PM.

Car manufacturers have been exploiting several routes in complying with these emissions regulations. Particulate filters for PM emissions, NO_x traps for NO_x emissions, selective catalytic reduction (SCR), electric cars, fuel-cell and solar vehicles are all possible means of getting round emissions legislation. However, limitations such as infrastructures, and high cost are concerns that need to be addressed. Furthermore, alternative fuel options namely compressed natural gas, liquid petroleum gas, hydrogen gas, etcetera are being utilised by dual-fuel engines piloted by diesel or gasoline. However, they are confronted by dearth of storing facilities [4]. Other methods that have been studied for the mitigation of NO_x emissions are the lean burn technique, retarding injection timing, water injection, multi-stage injection and Exhaust gas recirculation (EGR) [5].

Although, more improvements in present-day technical know-how have resulted in the advent of novel concepts directed towards reducing NO_x and PM emissions; nevertheless, there are still room for further exploits into new and customised solutions to the menace of engine-out emissions. In this study, past and current techniques of mitigating emissions of Diesel and gasoline engines are reviewed.

EMISSIONS AND CONTROL TECHNIQUES

The inevitable bye-products of the combustion of fuel and air are strongly reliant on upon parameters such as temperature, pressure, motion of the compressed air; the type, injection, atomisation, evaporation of the fuel and the interaction of these parameters [6]. Conventionally, the formation mechanisms of HC, CO, PM and NO_x in the combustion chamber strongly depend on temperature, local concentration of oxygen and duration of combustion as well; the first three increasing when temperature drops, while the fourth increases as temperature increases [7]. Hydrocarbon emissions emerge through two probable means in a Diesel engine. Firstly, when the local fuel and air blend is too lean to either burst into flames or sustain a spreading flame; and secondly, when the fuel and air mixture is too rich to ignite or sustain a burning flame. This accounts for the high unburnt hydrocarbon emissions.

Generally, the prevalent methods employed in mitigating engine-out emissions can be classified as hardware based, fuel based and combustion based solutions. Although, the hardware based solutions are

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prominent, the other two methods have lately elicited attention amidst researchers. In the sections and sub-sections below, some of the methods that are being adopted for the reduction of engine-out emissions are discussed.

HARDWARE BASED SOLUTIONS

A few of the hardware based solutions that are presented in the sub-sections include diesel particulate filters, selective catalytic reduction, NO_x trap and three-way catalytic converters with specific highlights of their merits and limitations.

Diesel particulate filters

With the advent of Euro V standards, particulate filters were presumed as essential for Diesel engines. Diesel particulate filters (DPF), which come in a varieties based upon the level of filtration required, eliminate PM in diesel exhaust by sifting exhaust from the engine. They are made of a ceramic matrix of silicon carbide, punched with microscopic conduits. A huge amount of particulates, between 90 and 99%, stick to the walls of these conduits as the emissions pass through them. The trapping of particulates blocks the channels; hence, the temperature of the filter needs elevation at steady interludes to burn off the particulates [8].

Selective catalytic reduction

Selective Catalytic Reduction (SCR) was initially used on stationary power plants and later on large engines. These days, it is fixed on new heavy-duty and light-duty Diesel vehicles in Europe. SCR reduces the oxides of nitrogen to nitrogen gas in a catalytic converter via ammonia, which is introduced as urea. The open-loop SCR systems can mitigate emissions of NO_x by 75-90% while closed-loop types used in stationary engines are capable of 95% cutbacks in NO_x emissions. SCR catalysts are combined with particulate filters for dual extenuation of PM and NO_x. They are capable of effectively mitigating 80% of HC emissions and 20-30% of PM emissions. The disadvantages of the SCR system, however, include added operational cost of urea and increased ammonia emissions [9].

NO_x trap

Due to the fact that Diesel engines run on lean-burn technique, three-way catalytic converters are not suitable in extenuating emissions of NO_x in Diesel applications. NO_x trap, an improved method suitable for Diesel engines, is commonly made of mineral zeolite, which adsorbs NO and NO_2 molecules. Furthermore, NO_x trap is utilised in meeting the emission standards in gasoline powertrains running on surplus air (lean-burn spark ignition engines).

The affluence of research on NO_x trap speaks volume of its acceptance as a method with the prospects of meeting stringent emissions indices. However, the shortcoming is that the material becomes easily saturated and loses its capacity to further capture NO_x emissions, thus necessitating intermittent restoration. A viable restoration method entails controlling combustion with surplus diesel for a few seconds [10].

Three-way catalytic converter

The three-way converter (TWC) has been the main technique used in extenuating emissions from petrol cars. It permits concurrent reduction of NO_x to nitrogen and oxygen, and oxidation of HC and CO. Before now, the prime predicament with three-way catalytic converter was during cold starts, where catalysts needed to attain a certain temperature (300-400°C) before effective catalytic operation could take place [10]. Recent advances in technology have, however, put that to rest. Although modern systems can attain this 'light-off' temperature within a few seconds, there may still be some emissions until that temperature is attained. Close-coupled catalysts, directly fitted after the engine exhaust manifold, permit the catalyst to start working immediately. With improved technology, the close-coupled catalyst method now satisfy the Euro 4, 5 and 6 standards [11]. However, for TWC to function efficiently, the engine must run with almost a stoichiometric air-fuel mixture. Once the engine runs close to the stoichiometric blend, in-cylinder temperature rises, which in turn heightens thermal stresses and knocking propensity [12]. Furthermore, elemental carbon are beyond the reach of catalytic converters, though they eliminate up to 90% of the soluble organic fraction (SOF). Hence, the residual particulates are scrubbed through a soot trap or diesel particulate filter [8].

Unfortunately, hardware based methods used for engine-out emissions such as SCR devices, particulate filters, three-way catalytic converters and NO_x traps are costly and add some intricacy to engine use.

COMBUSTION BASED SOLUTIONS

Studies have shown that exhaust emissions can be mitigated through improvements to combustion processes. Low temperature combustion technique and exhaust gas recirculation are discussed in the sub-sections below with explicit focus on their merits and limits.

Low temperature combustion (LTC) technique

In recent times, researchers have tried to mitigate engine-out emissions through modification of combustion processes. An instance of this is the LTC technique [13] such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and partially premixed compression ignition (PPCI) engines. Kobayashi *et al* [14] studied the impacts of a turbo-charged natural gas HCCI engine on combustion and emissions. They reported a NO_x emission factor of 0.096 g/kWh, an extremely low value and thus concluded that it was unnecessary to install exhaust treatment equipment. In his work on HCCI for future gasoline powertrains, [15] reported that HCCI operation produced 99% reduction in NO_x when compared with baseline direct injection gasoline engine mode. Conversely, HC emissions for

HCCI operation were found to be within the same range with direct injection gasoline engine mode.

Nonetheless, there are a few glitches to be solved before the commercial application of HCCI becomes feasible. Whereas it is crucial to control combustion for best fuel economy and ultra-low emissions; ironically, HCCI engine does not have a direct mode to control the ignition timing. Other hurdles include difficulty in extending the operating range of HCCI combustion to high loads, high HC and CO emissions mostly at low loads, high rates of heat release and increase in NO_x emission at high loads [16]–[18]. While, the viability of a full fledge HCCI Diesel engine had been established in a single-cylinder heavy-duty Caterpillar engine [19], the extension of full load HCCI application to light duty engines remains vague [20].

Another promising method to ultra-low emissions is PCCI, which depends on late injections and high EGR rates in delaying auto-ignition. In addition to lowering emissions of NO_x and soot, PCCI displays fewer emissions of HC and CO when compared to HCCI. In a work to determine the effects of compression ratio on exhaust emissions from a PCCI Diesel engine, [21] established that, with negligible CO and HC penalty, decreasing the compression ratio or impeding the injection timing noticeably lessened emissions of NO_x and soot when both premixed and diffusion-combustion stages were present. However, the constraints with PCCI are the difficulty in attaining it at high engine loads, cold-start problems, significant emissions of CO and HC, which make the use of catalysts imperative in PCCI [22].

Exhaust gas recirculation (EGR)

The three-way catalytic converter is not suitable for of reduction NO_x emissions in a Diesel engine because the engine works with excess air. Alternatively, EGR has been widely utilised in reducing NO_x emissions. The technique involves recirculating a certain proportion of the exhaust gas into the inlet air so as to lessen the oxygen content and in-cylinder temperature. Hence, addition of exhaust gas reduces the partial pressure of O_2 and ambient nitrogen in the incoming blend, which subsequently causes a decline in the production of NO_x [23].

While it aids in considerably reducing NO_x emissions, EGR has certain shortcomings. Retarded combustion and increased soot production are noticeable drawbacks. Since a reduction in O_2 concentration and temperature enhances the emission of unburnt HC and CO, EGR reduces NO_x productions at the expense of increase in the productions of HC, CO and PM [24]. Furthermore, there is a limit to the application of EGR, around 35%, prompting extra measures in order to abide by regulations.

FUEL BASED SOLUTIONS

Appropriate modifications to the types of fuel and its composition hold enormous prospects in the quest for an enduring solutions to the menace of engine-out emissions. The economy, flexibility, efficacy and the ease of retrofitting into existing engines make this method unique. Although there are several instances of this method in literature, for the essence of brevity Natural gas/Diesel dual-fuel technique, simulating EGR through CO_2, Biogas/Diesel dual-fuel, and Liquefied Petroleum Gas (LPG)–Diesel dual-fuel are discussed.

Natural gas/diesel dual-fuel technique

Natural gas, usually stored at 20MPa, has been widely recognised as an ideal substitute to crude oils because of the merit of clean burning [25]. Since the carbon mass percentage in natural gas is about 75% compared to 86-88% for both petrol and diesel, the low carbon-to-hydrogen ratio in natural gas engines ensures lower emissions of CO_2, CO and HC than petrol or Diesel engines per unit energy released [26], [27]. In addition, the burning of natural gas virtually produces no particulates since it contains less dissolved impurities [28].

Researchers [29] reported that the substitution of diesel oil with natural gas yielded reduced in-cylinder pressure and total brake specific fuel consumption, decreased NO_x, PM and CO_2 emissions in contrast to the combustion of diesel oil, with trade-off in CO and HC emissions. Gharehghani *et al.* [30] found that a mitigation in emissions of NO_x is attainable through the enhancement of the swirl ratio at the intake side of dual-fuel engines, possibly because of the upsurge in loss of heat when swirl rises. They reported substantial drop in NO_x when engine load was high with lower mass ratio of natural gas, whereas lesser PM were emitted at lower load and higher mass ratio of natural gas. However, both emissions and performance deteriorated because of the very lean blend at lower loads.

Simulating EGR through CO_2

Modest attempts have been made at using CO_2 in simulating EGR. In the work of [31], adding CO_2 to the air intake suitably moderated NO_x and soot productions and the price tag of cooling system used in EGR. The effect of increasing EGR in Diesel engine on the resultant NO_x and PM emissions was also discussed in [32] as illustrated in Figure-1. The large amount of soot in higher EGR percentage was ascribed to lower performance owing to drop in oxygen concentration, and soot accumulation due to the recirculation of exhaust gas through many cycles as well.

Furthermore, Çinar *et al*. [33] studied the effects of introducing CO_2 as a diluting gas and injection pressure on performance and emissions. CO_2, as a diluting gas was injected via the inlet charge of a Diesel engine at 2%, 4% and 6% separately. They found that whereas NO_x emissions were reduced with CO_2 injection, other parameters worsened. The injection of 6% CO_2, resulted in depreciation of torque, power, *bmep* and *bsfc* by 5.9%, 5.5%, 6%, and 3.3% in turn. Smoke emissions rose roughly by 60%, whereas CO emissions went up 8.5 folds. Nevertheless, NO_x emissions dropped by nearly 50% at the injection of 6% CO_2.

VOL. 11, NO. 22, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

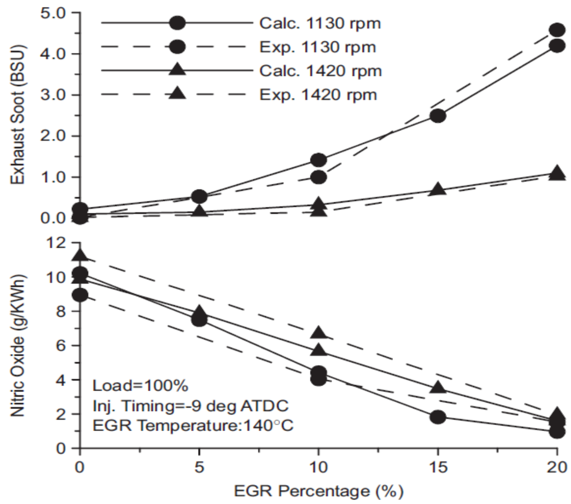

Figure-1. Effect of EGR rate on calculated and measured NO and soot emissions [32]

Biogas/diesel dual-fuel

In Duc & Wattanavichien [34] the effect of a small IDI biogas premixed charge diesel dual-fuelled CI engine used in agricultural applications on combustion and emissions by varying engine loads and EGR percentages were investigated. They found that biogas-diesel dual-fuelling of HCCI engine revealed almost no deterioration in engine performance at all test speeds. Lower energy conversion efficiency was recorded, which was offset by the reduced fuel cost of biogas over diesel.

The potential of effective utilisation of biogas in HCCI engine using a single-cylinder Diesel engine modified to run in HCCI mode was examined by Nathan *et al* [35]. The varied parameters were charge temperature and diesel injection quantity. He reported that the CO_2 in the biogas suppressed the high heat release (HHR) prevalent in HCCI engines fuelled with diesel. Thermal efficiencies close to Diesel engine operation along with extremely low levels of NO_x ($\leq$ 20 ppm) and smoke ($\leq$ 0.1 BSU) were attained in a BMEP range of 2.5 to 4 bar. HC emissions were very high but were lowered when the charge temperature was raised. The thermal efficiency at a BMEP of 4 bar was 27.2% in the biogas-diesel HCCI mode as against 30% with diesel operation.

Liquefied petroleum gas (LPG) – diesel dual-fuel

In a study conducted by Qi *et al*. [36], the effects of LPG–Diesel blended fuel on the performance and pollutant emissions of a DI Diesel engine were investigated. Their findings revealed that upsurge in LPG by mass fraction in the blended fuel resulted in lower peak cylinder pressure. Contrary to Diesel operation, at low engine load, equivalent *bsfc* deteriorated under blended fuel mode. However, at high load, equivalent *bsfc* values were close to the values recorded under Diesel operation. They reported that there was a drop in NO_x emissions as the mass fraction of the LPG fraction in the blended fuel increased; yielding lower NO_x emissions when compared to Diesel operation. Furthermore, at high engine load there was a significant reduction in CO emissions as the mass fraction of the LPG fraction increased. However, a slight increase in CO emissions was recorded at low engine load. Emissions of HC marginally increased with upsurge in the mass fraction of the LPG fraction in the blended fuel.

Hence, LPG–Diesel blended fuel is a promising technique for controlling engine-out emissions especially NO_x and smoke. This is particularly significant in view of the teething troubles of controlling NO_x and smoke emissions on Diesel engines. The drawback in equivalent *bsfc* is partly traded-off by the relative affordability of LPG.

CONCLUSIONS

A study was carried out to appraise the measures that are being instituted by regulatory bodies in contending the threat of engine-out emissions, the responses of stakeholders in the automotive industry in terms of research and development, the economy along with the aptness of the measures and strategies put in place towards extenuating engine-out emissions. Though, growths in technical expertise have brought about unique concepts, intended at reductions of NO_x and PM emissions; nevertheless, findings revealed that there were no one-size-fits-all solutions so far in place; most of the existing solutions enjoy, at best, relative advantages over one another. However, it is noteworthy that the fuel based and combustion based methods hold vast prospects in the pursuit of lasting panacea to the menace of engine-out emissions. Hence, there are openings for exploits in these areas in finding viable solutions to engine-out emissions.

REFERENCES

[1] World Health Organisation, '"Air quality and health Fact sheet No 313"', Geneva, Switzerland: World Health Organisation, 2011.

[2] J. Watts, 'China: the air pollution capital of the world', The Lancet, vol. 366, no. 9499. pp. 1761–1762, 19-Nov-2005.

[3] The European Union, 'Commission Regulation (EC) No. 692/2008', Off. J. Eur. Union, L 199, 1-135., 2008.

[4] A. Garvine, '"One Giant Leap", Interview of Armstrong', Engine Technol. Int., no. Issue 3/2002, pp. pp. 20–23, 2002.

[5] V. Pirouzpanah and R. K. Sarai, 'Reduction of emissions in an automotive direct injection diesel engine dual-fuelled with natural gas by using variable exhaust gas recirculation', Proc. Inst. Mech. Eng. Part D J. Automob. Eng., vol. 217, no. 8, pp. 719–725, 2003.

ARPN Journal of Engineering and Applied Sciences

[6] O. Laguitton, 'Advanced Diesel Combustion Strategies for Ultra-Low Emissions', University of Brighton, United Kingdom, 2005.

[7] J. B. Heywood, Internal combustion engine fundamentals. New York: McGraw-Hill, 1988.

[8] MECA, 'Emission Control Technologies for Off-Road Diesel Equipment', Manufacturers of Emission Controls Association, 2012. [Online]. Available: http://www.meca.org/cs/root/emission_control_technology/offroad_diesel_equipment.

[9] J. Zhang, 'Catalytic Converter – Part I of Automotive After-treatment System', 2010. [Online]. Available: http://www.bowmannz.com/yahoo_site_admin/assets/docs/CatalyticConverter.92123507.pdf. [Accessed: 12-Nov-2027].

[10] K. Lindqvist, 'Emission standards for light and heavy road vehicles', The Air Pollution & Climate, Göteborg, Sweden, 25, 2012.

[11] C. Favre, J. May, and D. Bosteels, 'Emissions Control Technologies to Meet Current and Future European Vehicle Emissions Legislation', Brussels, Belgium, 2012.

[12] A. Ibrahim and S. Bari, 'Effect of Varying Compression Ratio on a Natural Gas SI Engine Performance in the Presence of EGR', Energy & Fuels, vol. 23, no. 10, pp. 4949–4956, Oct. 2009.

[13] J. E. Dec, 'Advanced compression-ignition engines—understanding the in-cylinder processes', Proc. Combust. Inst., vol. 32, no. 2, pp. 2727–2742, 2009.

[14] K. Kobayashi, T. Sako, S. Morimoto, S. Kanematsu, K. Suzuki, T. Nakazono, and H. Ohtsubo, 'Development of HCCI natural gas engines', J. Nat. Gas Sci. Eng., vol. 3, no. 5, pp. 651–656, Oct. 2011.

[15] R. J. Osborne, G. Li, S. M. Sapsford, J. Stokes, T. H. Lake, and M. R. Heikal, 'Evaluation of HCCI for Future Gasoline Powertrains', SAE 2003-01-0750, 2003, 2003.

[16] S. Khalilarya, S. Jafarmadar, H. Khatamnezhad, G. Javadirad, and M. Pourfallah, 'Simultaneously Reduction of NOx and Soot Emissions in a DI Heavy Duty diesel Engine Operating at High Cooled EGR Rates', Int. J. Aerosp. Mech. Eng., vol. 6, no. 1, pp. 26–34, 2012.

[17] J. Ma, X. Lü, L. Ji, and Z. Huang, 'An experimental study of HCCI-DI combustion and emissions in a diesel engine with dual fuel', Int. J. Therm. Sci., vol. 47, no. 9, pp. 1235–1242, Sep. 2008.

[18] M. Yao, Z. Zheng, and H. Liu, 'Progress and recent trends in homogeneous charge compression ignition (HCCI) engines', Prog. Energy Combust. Sci., vol. 35, no. 5, pp. 398–437, 2009.

[19] K. Duffy, A. Kieser, and E. Fluga, 'Heavy duty HCCI development activities.' in In: 2004 Directions in Engine-Efficiency and Emissions Research (DEER) conference;, 2004.

[20] S. Gan, H. K. Ng, and K. M. Pang, 'Homogeneous Charge Compression Ignition (HCCI) combustion: Implementation and effects on pollutants in direct injection diesel engines', Appl. Energy, vol. 88, no. 3, pp. 559–567, 2011.

[21] O. Laguitton, C. Crua, T. Cowell, M. R. Heikal, and M. R. Gold, 'The effect of compression ratio on exhaust emissions from a PCCI diesel engine', Energy Convers. Manag., vol. 48, no. 11, pp. 2918–2924, 2007.

[22] J. E. Parks, V. Prikhodko, J. M. E. Storey, T. L. Barone, S. a. Lewis, M. D. Kass, and S. P. Huff, 'Emissions from premixed charge compression ignition (PCCI) combustion and affect on emission control devices', Catal. Today, vol. 151, no. 3–4, pp. 278–284, Jun. 2010.

[23] A. Paykani, R. K. Saray, A. M. Kousha, and M. T. S. Tabar, 'Performance and Emission Characteristics of Dual Fuel Engines at Part Loads Using Simultaneous Effect of Exhaust Gas Recirculation and Pre-Heating of Inlet Air', Int. J. Automot. Eng., vol. 1, no. 2, 2011.

[24] V. Peixoto, C. Argachoy, I. Trindade, and M. Airoldi, 'Combustion Optimization of a Diesel Engine with EGR system using 1D and 3D simulation tools', Fourth Eur. Combust. Meet. Vienna, 2009.

[25] W. A. Abdelghaffar, 'Performance and Emissions of a Diesel Engine Converted to Dual Diesel-CNG Fuelling', Eur. J. Sci. Res., vol. 56, no. 2, pp. 279–293, 2011.

[26] A. K. Sen, S. K. Ash, B. Huang, and Z. Huang, 'Effect of exhaust gas recirculation on the cycle-to-cycle variations in a natural gas spark ignition engine', Appl. Therm. Eng., vol. 31, no. 14–15, pp. 2247–2253, Oct. 2011.

[27] Rabl, 'Environmental benefits of natural gas for buses', Transp. Res. Part D Transp. Environ., vol. 7, no. 6, pp. 391–405, Nov. 2002.

[28] R. G. Papagiannakis and D. T. Hountalas, 'Experimental investigation concerning the effect of natural gas percentage on performance and emissions

of a DI dual fuel diesel engine', Appl. Therm. Eng., vol. 23, no. 3, pp. 353–365, 2003.

[29] R. G. Papagiannakis and D. T. Hountalas, 'Combustion and exhaust emission characteristics of a dual fuel compression ignition engine operated with pilot Diesel fuel and natural gas', Energy Convers. Manag., vol. 45, no. 18–19, pp. 2971–2987, 2004.

[30] A. Gharehghani, S. M. Mirsalim, and S. A. Jazayeri, 'Numerical and Experimental Investigation of Combustion and Knock in a Dual Fuel Gas/Diesel Compression Ignition Engine', J. Combust., vol. 2012, pp. 1–10, 2012.

[31] H. Zhao, J. Hu, and N. Ladommatos, 'In-cylinder studies of the effects of CO_2 in exhaust gas recirculation on diesel combustion and emissions', Proc. Inst. Mech. Eng. Part D J. Automob. Eng., vol. 214, no. 4, pp. 405–419, 2000.

[32] D. T. Hountalas, G. C. Mavropoulos, and K. B. Binder, 'Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions', 19th Int. Conf. Effic. Cost, Optim. Simul. Environ. Impactof Energy Syst. ECOS 2006, vol. 33, no. 2, pp. 272–283, 2008.

[33] Çinar, T. Topgül, M. Ciniviz, and C. Haşimoğlu, 'Effects of injection pressure and intake CO2 concentration on performance and emission parameters of an IDI turbocharged diesel engine', Appl. Therm. Eng., vol. 25, no. 11–12, pp. 1854–1862, 2005.

[34] P. M. Duc and K. Wattanavichien, 'Study on biogas premixed charge diesel dual fuelled engine', Energy Convers. Manag., vol. 48, no. 8, pp. 2286–2308, Aug. 2007.

[35] S. Swami Nathan, J. M. Mallikarjuna, and A. Ramesh, 'An experimental study of the biogas–diesel HCCI mode of engine operation', Energy Convers. Manag., vol. 51, no. 7, pp. 1347–1353, Jul. 2010.

[36] H. Qi, Y. Z. H. Bian, Z. H. Y. Ma, C. H. H. Zhang, and S. H. Q. Liu, 'Combustion and exhaust emission characteristics of a compression ignition engine using liquefied petroleum gas–Diesel blended fuel', Energy Convers. Manag., vol. 48, no. 2, pp. 500–509, 2007.