

A Review of the Utilisation of Natural Gas with High Carbon Dioxide Content as Automotive Fuel in an Indirect Injection Diesel Engine

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Abstract. The persistent consumption of fossil fuels by modern transportation tends toward feared depletion in crude oil and infliction of health risks on human beings and the environment due to the noxious emissions from the combustion of fossil fuels. This work examines the prospects of fuel modification in improving engine performance by utilising compressed natural gas (CNG) mixed with varying proportions of carbon dioxide (CO₂) as fuel in Diesel engines. The extent to which the addition of CO₂ to CNG could help simulate the effects of exhaust gas recirculation (EGR) as employed in modern engine technology will be established.

Keywords: indirect injection, compressed natural gas, CO₂, engine performance, emissions

1 Introduction

Although Diesel engines are the most reliable and fuel-efficient internal combustion engines in the automotive industry; its high emissions drawbacks and the rising cost of fossil fuels have elicited concerns among automotive engineers. In response to health issues, the European Union has introduced stringent emission standards to regulate atmospheric pollutants such as PM, NO_x and HC for vehicles sold in the EU market [1]. Consequently, the past decades have witnessed upsurges in modern engine technology, which are aimed at utilising alternative fuels and hence, abating emissions from Diesel engines, such as advanced fuel injection equipment, piezo-injection, injector nozzle modification, after-treatment devices and etc. [2]–[6]. However, in spite of encouraging results, these technologies come with high price tags; the cost and complexity in retrofitting them in to existing engines, therefore, threaten the competitiveness of the Diesel engine package.

Further advances in modern engine technology have led to the emergence of the low temperature combustion techniques, which are aimed at improved fuel consumption and reduced emissions through modification of combustion processes [7]. These include homogeneous charge compression ignition (HCCI) [8]–[10], premixed charge compression ignition (PCCI) [5], [11], [12], partially premixed charge compression ignition (PPCI) engines [13] and EGR [14], [15]. HCCI and PCCI engines demonstrate pronounced capabilities in terms of simultaneous ultra-low NO_x and PM emissions.

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However, HCCI engines are inhibited by obstacles such as combustion control, high HC and CO emissions at low loads, increase in NO_x emission at high loads, high rates of heat release and etc. [5], [14], [16]–[18]. PCCI, on other hand, is difficult to achieve at high engine loads; this fact combined with cold start challenges and the higher CO and HC emissions have resulted in the use of catalysts in PCCI operation [19]. In spite of the retinue of advancements in research over the last decade, large scale adoption of HCCI Diesel engines in commercial vehicles is presently not feasible [20].

Recently, dual-fuel combustion techniques, which often consider modification of the fuel itself in controlling combustion processes, and hence engine-out emissions, have elicited varied investigations and applications. For instance, studies have revealed that, in addition to improved fuel economy, the dual-fuel combustion concept utilising CNG/Diesel is found supportive in the mitigation of pollutant emissions from Diesel engines [21]–[23]. Usually, a carburetted mixture of air and high octane gaseous fuel (e.g. natural gas), prepared in an external mixing device, is compressed and inducted into the engine cylinders. The compressed mixture of air and natural gas does not auto-ignite due to its high auto-ignition temperature. Therefore, a pilot amount of diesel fuel is injected into the cylinders near the top dead centre (TDC) of the compression stroke. After a short ignition delay, the combustion of diesel occurs first; igniting the natural gas, and then the flame propagation begins. The presence of compressed natural gas (CNG) in the charge reduces the cylinder temperature due to lean combustion, which subsequently results in lower NO_x and PM emissions. Hence, this work examines the prospects of fuel modification in improving engine performance and abating engine-out emissions, by utilising compressed natural gas (CNG) mixed with varying proportions of carbon dioxide (CO₂) as fuel in Diesel engines.

2 CNG-CO₂/Diesel dual-fuel combustion

As aptly expressed by [23], dual-fuel combustion, using CNG/Diesel as base fuel, is currently restored in the exertion to overcome the difficulties of HCCI engines, NO_x, PM and CO emissions, which is really difficult to achieve in Diesel engines. The technique reduces the quantity of diesel consumption and hence, results in cleaner combustion due to the low C/H ratio [24]. Extensive researches have revealed that substitution of diesel fuel by natural gas, under dual-fuel mode, yield lower peak cylinder pressure, lesser brake specific fuel consumption (*bsfc*) and reduced NO_x, CO₂ and PM emissions when compared to normal diesel combustion with some trade-off in emission levels of CO and HC [23].

Gharehghani et al. [25] reported that by increasing the intake swirl ratio in dual-fuel engines, a significant reduction in NO_x was achieved at high engine load with lower mass ratio of natural gas, while lower PM was recorded at lower load and higher mass ratio of natural gas. At part load, the total *bsfc* was considerably higher under dual-fuel mode due to the low combustion rate of gaseous fuel. However, at lower loads, both emission and combustion performance suffered due to the extremely lean mixture and incomplete combustion in the dual-fuel mode. To resolve the light load performance problem, [26] introduced 15% cooled EGR into a dual-fuel Diesel engine, which led to visible reduction in the exhaust emissions of NO_x, CO and HC. Although it helps to noticeably reduce NO_x emissions, EGR has certain shortcomings in Diesel engines. The drop in oxygen and overall temperature favours the release of unburned HC and CO; hence, it mitigates NO_x emissions at the expense of rise in the emissions of HC, CO and PM [27]. Moreover, there is a bound to EGR technology, which is about 35%, necessitating further treatment of exhaust gases in order to keep pace with emissions standards.

Furthermore, CO₂ was used in simulating the effects of EGR by [28]. Their findings showed that CO₂ addition was suitable in extenuating NO_x and soot emissions and the cost of EGR cooling system. Jin et al [29] used four different CO₂ mass fractions in diesel fuel, namely, 3.13%, 7.18%, 12.33% and 17.82% to study the effect of CO₂ concentration on jet flame characteristics. They reported that the dilution and atomisation effects of the dissolved CO₂ component in the fuel had a great influence on the flame structure. At the same injected pressure, the low temperature flame length increased with increase in CO₂ concentration in the fuel and vice-versa. The mean temperature of the flame increased

and then dropped with increase in CO₂ concentration at the same injected pressure. In a related work, the effects of in-cylinder injection of CO₂ on PCCI combustion were investigated by [30]. They found that for in-cylinder injection of CO₂, either advancing CO₂ injection timing or increasing cyclic injection quantity greatly reduced the emission of NO_x with little loss in the thermal efficiency. With increase in the CO₂ injection quantity, intake pipe injection had a similar effect to EGR, that is, reduction in NO_x and increase in PM emission [30].

Moreover, Çinar et al [31] investigated the effect of CO₂ as a diluent in the intake manifold and injection pressure on engine torque, power, *bmep*, specific fuel consumption (*sfc*), CO, PM and NO_x emissions. In this study, CO₂, used as diluent, was injected into the intake manifold of a Diesel engine at a ratio of 2%, 4% and 6% respectively. The research outcomes revealed that while NO_x emission improved with CO₂ admission in the inlet charge, other parameters deteriorated. With 6% CO₂ admission, engine torque, power, *bmep* and *bsfc* approximately deteriorated by 5.9%, 5.5%, 6%, and 3.3% respectively; smoke emission increased approximately by 60% while CO emission increased approximately by 8.5 times from its base level. In spite of all these, NO_x emission reduced approximately by 50% at 6% admission of CO₂. In the work of Bedoya et al. [32], the effects of mixing system and the pilot fuel quality on performance using biogas (60% CH₄ + 40% CO₂) as primary fuel in a stationary, dual-fuel Diesel engine were investigated. Their findings revealed that full diesel substitution was attainable using biogas and biodiesel as power sources for all loads evaluated. Thermal efficiency and substitution of pilot fuel were increased, while CH₄ and CO emissions were reduced by using supercharged mixing system combined with biodiesel as pilot fuel.

3 Inferences from literature

Inferences from literature revealed that existing literature and data on combustion, performance, in-cylinder pressure and temperature; rate of heat release; emissions and other parameters characterising CNG-CO₂/Diesel dual-fuel combustion in Diesel engine are inadequate. Natural gas, a clean fuel, possesses impressive tolerance for high compression without resultant knocking in IC engines. On the other hand, the heat absorbing capacity of CO₂ makes it a good diluent, which lowers in-cylinder temperature and pressure, the major precursor of NO_x emissions, during combustion. Hence, CNG is intended at minimising emissions, which are directly related to the combustion of diesel fuel, while the addition of CO₂ acts as EGR. Depending on the engine speed and load, CNG appreciably influences engine performance and emissions. The effect of increasing EGR in Diesel engine on the resultant NO_x and PM emissions was discussed in [33] as illustrated in Figure 1. The large amount of soot in higher EGR percentage was attributed to lower performance due to reduction in oxygen concentration, and soot accumulation due to the recirculation of exhaust gas through many cycles as well. The possibility, therefore, exists that subject to the fine tuning of the various parameters influencing engine operation, CNG-CO₂ replacing as fuel in a Diesel engine could well achieve improved fuel efficiency and equally discharge the roles of EGR, with tolerable compromise in performance. Expectedly, reductions in NO_x emissions may be achieved; while PM emissions could also be reduced.

4 The natural gas deposits in Malaysia and CNG-CO₂/Diesel engine combustion

The natural gas deposits in Malaysia is characterised as sour because of the high CO₂ content, which is in the range of 12-40% by chemical composition [34]; hence, they are not readily exploitable in automobiles as the high CO₂ content can significantly retard in-cylinder temperature and pressure, with attendant adverse effects on engine performance. Undoubtedly, capturing CO₂ from natural gas is a capital intensive venture. Hence, arising from the high cost of capturing CO₂ from natural gas and the perennial engine emissions, modifying the morphology of Diesel engine that can accommodate the usage of untreated natural gas appears to be a cheaper alternative. The possibility, therefore, exists that

subject to the fine tuning of the various parameters influencing engine operation, CNG-CO₂/Diesel as fuel in a Diesel engine could function well as automobile fuel with tolerable compromise in performance. Furthermore, the high heat absorbing capacity of CO₂ reduces oxygen concentration and thus, lowers in-cylinder temperature, the major precursor of NO_x emissions during combustion.

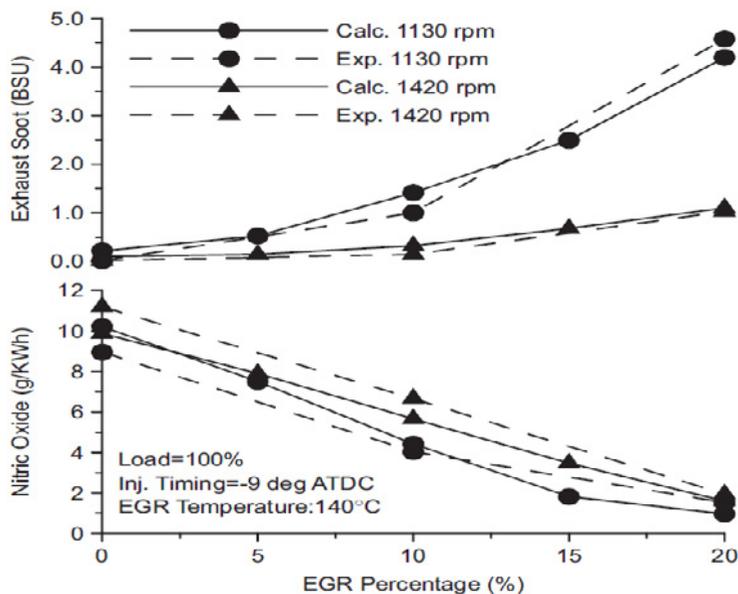


Figure 1. Effect of EGR rate on calculated and measured NO and soot emissions [33]

5 Materials and methods

A four-cylinder IDI Diesel engine will have its intake port modified to accommodate the injection system for CNG-CO₂ gases. The CNG and CO₂, from separate cylinders at different proportions, will be mixed in a fuel mixing chamber and injected into the cylinder through the intake port of the engine. As the charge is compressed in the cylinder, a pilot amount of diesel will be injected near the end of compression stroke to initiate ignition. The brake specific fuel consumption (bsfc) and the cylinder pressure history, will be identified directly from the engine control unit. Other engine parameters to be studied are NO_x, CO, unburned HC, and total particulate matter (PM). Engine performance analysis would be carried out for specified engine speeds and loads in three different operation modes. The normal diesel combustion analysis tests will be taken as baseline performance data for the comparison and analysis of the other two modes.

5 Conclusion

Although the dual-fuel application on Diesel engine using CNG as fuel with pilot diesel injection is known, adding CO₂ to the system to improve fuel economy and mitigate emissions is yet to be fully exploited. The natural gas, with CO₂ addition, could replace a significant portion of the diesel fuel; and possibly, result in lower brake specific fuel consumption (bsfc) value. This concept can be applied on existing engines which do not have EGR system to mitigate emissions with improved or at least maintained fuel efficiency comparable to the conventional Diesel engine since the presence of CO₂ in the CNG simulates the effects of EGR. Moreover, it avoids the use of cooling unit and the problem of growing soot concentration in subsequent cycles since it is cleaner than EGR. Furthermore, it is

expected that the high cost associated with the capture of CO₂ from natural gas could be eliminated since this concept employs CNG with substantial CO₂ content. Ultimately, a breakthrough in experimental work may trigger the mass utilisation of the abundant natural gas deposit in Malaysia in its raw form, which has for long remained mostly untapped.

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