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# Comparative study on EGR and lean burn strategies employed in an SI engine fueled by low calorific gas

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## HIGHLIGHTS

- EGR has a narrower window of dilution than lean burn in low-Btu gas engines.
- Lean burn shows more intensive heat release and higher peak than EGR.
- EGR affects the $O_2$ fraction rather than specific heat in a low-Btu gas engine.
- EGR is effective in $NO_x$ reduction, but it also increases THC faster.
- Lean burn shows higher efficiency than EGR while meeting the legal standard.

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## ABSTRACT

In this study, a naturally aspirated spark ignition engine fueled by low calorific gas (LCG) was tested in both exhaust gas recirculation (EGR) and lean burn modes, and the effects of these modes on engine performance and combustion and emission characteristics were evaluated and compared. The LCG, composed of 40% natural gas (NG) and 60% nitrogen ($N_2$), was used as the main fuel, and a dilution rate was employed to carry out a comparison between the two modes under identical levels of dilution. The engine test results demonstrate that the dilution range was narrower when running with EGR at stoichiometry than when running with lean burn, while more intensive heat release and higher peaks were obtained in lean burn than in EGR under similar operating conditions. Analysis of the in-cylinder mixture condition shows that introducing EGR to an LCG engine mainly affected the $O_2$ fraction rather than the specific heat, owing to the presence of a large amount of inert gas. This is one of the major reasons for the difference in combustion characteristics between EGR and excess air operations. The engine test results also indicate that an improvement in thermal efficiency was possible in the lean burn mode when using LCG fuel, whereas the use of EGR barely improved inferior fuel economy. EGR was more effective in reducing $NO_x$ emissions, but it also increased total hydrocarbon emissions faster. Lean burn as well as EGR successfully satisfied the legal emission regulation when the level of dilution was increased to the dilution limit, although there was a slight reduction in efficiency.



## 1. Introduction

The use of renewable fuels in power generation systems has been considered as one of the effective ways to reduce greenhouse gases as well as to resolve energy security concerns. Bio-originated low calorific gas (LCG) such as biogas or landfill gas is one such fuel that can be obtained from the anaerobic bacteria decomposition of biomasses or organic waste materials. It is usually composed of 40–60% of combustible gases (mostly methane ($CH_4$)), incombustible gases such as nitrogen ($N_2$) and carbon dioxide ($CO_2$), and various non-methane organic compounds. Since LCG contains $CH_4$, it can be utilized as a fuel in internal combustion (IC) engines in order to generate electricity [1–3]. Considering that the 20-year global warming potential (GWP) of $CH_4$ is 72 [4], utilizing LCG in power generation systems can significantly ease environmental concerns. Moreover, in developing countries, the deployment of

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engines that can use this fuel without additional treatment to eliminate non-flammable components would be beneficial to keep production costs low.

To improve the performance and exhaust emissions of LCG engines, two inlet charge dilution strategies can be considered: "lean burn" and "exhaust gas recirculation (EGR)". With respect to the former strategy, considerable studies have been conducted since the early 1980s to extend the lean operation limit of natural gas (NG) engines by realizing in-cylinder charge stratification and/or developing fast burning combustion cylinders. As a result, a lean burn can simultaneously achieve higher thermal efficiency, longer durability, and lower engine-out nitrogen oxides ($NO_x$) emissions [5]. Recently, however, the legal standard for harmful combustion products has become increasingly stringent and it is more difficult to produce even lower emissions without deteriorating engine performance. For instance, one way to reduce the level of engine-out $NO_x$ further is to use leaner air/fuel mixtures. However, this technique demands engine operations near the misfire limit, which means that the combustion stability may get worse. This unstable combustion increases total hydrocarbon (THC) and carbon monoxide (CO) emissions and exacerbates cyclic variations, ultimately decreasing the engine efficiency. Another way to control emissions is to retard the spark ignition timing while maintaining the other operating conditions. This can result in lesser $NO_x$ emissions by lowering the combustion temperature and decreasing the reaction time for $NO_x$ formation without disturbing combustion stability. However, this strategy also reduces the engine thermal efficiency because the power output is decreased compared to that of the maximum brake torque (MBT) spark advance timing. These points suggest that any efforts to achieve further reduction in $NO_x$ emissions would be accompanied by a decrease in the engine thermal efficiency and an increase in THC emissions [5,6]. It is therefore difficult to satisfy the legal $NO_x$ emission standard in the lean burn operation mode without using expensive exhaust gas aftertreatment systems such as selective catalytic reduction (SCR) and an oxidation catalyst.

The latter charge dilution strategy, EGR, can be an alternative to the lean burn strategy. In spark ignition (SI) engines, EGR can be achieved by introducing some of the combustion product gas back into the incoming mixture as an additional charge by opening the throttle. This recirculated exhaust gas has several effects on the in-cylinder combustion. It increases inlet thermal capacity owing to an increased charge gas quantity and higher specific heat capacity, decreases oxygen ($O_2$) concentration of the incoming mixture by exhaust gas dilution at the inlet, and induces endothermic dissociation reaction of $CO_2$ and/or water vapor ($H_2O$) [7,8]. All these effects lower the flame temperature and the $O_2$ partial pressure, leading to a decrease in $NO_x$ formation. A decrease in knocking tendency is another advantage of the use of EGR. This allows the use of turbocharging, a relatively high compression ratio, and operations in the MBT spark timing, all of which can accomplish a higher thermal efficiency.

EGR is generally added to a stoichiometric air/fuel mixture. Therefore, the most significant benefit in terms of emission reductions can be obtained when EGR is combined with a three-way catalyst (TWC). The TWC is well known for its capability of suppressing $NO_x$, THC, and CO emissions simultaneously. Moreover, it is much cheaper than the SCR devices used in lean burn engines. Hence, the combination of EGR and TWC can be a more economical alternative to produce lower emissions than lean burn with SCR.

Unlike emissions, it is not quite clear which charge dilution method is superior in terms of improving the engine performance. Several NG engine studies have been conducted on this issue, but they reported somewhat conflicting results on performance parameters such as the thermal efficiency. For example, Ibrahim and Bari [5] conducted a numerical simulation of a 4-stroke SI natural gas engine together with experimental validations. They found that the power loss of the EGR dilution was higher than that of excess air at the same level of dilution, whereas the use of the former was more effective in achieving lower NO emission than the latter. On the contrary, Nellen and Boulouchos [9] concluded that the use of cooled EGR with a TWC was superior to lean burn operation with an oxidation catalyst for both engine performance and emissions when using a turbocharged NG engine. In addition, some other researchers showed that a similar level of maximum thermal efficiency was obtained for both EGR and lean burn operations [10].

Unlike NG engines, however, to the best of our knowledge, there are no comparative studies on EGR and lean burn strategies in LCG engines. Therefore, in this study, a naturally aspirated SI engine fueled by LCG with 40% NG was tested in both the EGR and the lean burn modes and their effects on engine performance and on combustion and emission characteristics were evaluated and compared. As an important result, the EGR and lean burn strategies were compared at identical levels of dilution, and their applicability was discussed in terms of maximizing thermal efficiency and satisfying the $NO_x$ emission regulation.

## 2. Experimental procedure

### 2.1. Experimental setup

A natural gas engine (GE08TI) from Doosan Infracore was selected as a base engine and modified for the use of an LCG (refer to Section 2.1 in our previous study [6] for details of the changes). Fig. 1 shows a schematic of the experimental setup and Table 1 lists the engine specifications. The engine was connected to a direct current dynamometer system (Schenck) in order to control its speeds and loads. The gaseous emissions were detected by a gas analyzing system (AMA i60, AVL) and excess air ratio (EAR), which is the actual air/fuel ratio divided by the stoichiometric air/fuel ratio, was obtained using a wide band lambda meter (LA4, ETAS) placed in the exhaust pipe. The crankshaft position was measured by an encoder (E40S8, Autonics) and the cylinder pressure was detected using a spark-plug-type piezoelectric pressure transducer (Type 6117B, Kistler) and a charge amplifier (Type 5018A, Kistler). The signals from the encoder and pressure sensor were logged and analyzed by a real-time combustion analyzer (DEWE-800, Dewetron) in order to understand in-cylinder combustion phenomena. Engine operation and status data were displayed and recorded by a data acquisition device (GL800, Graphtec).

An LCG was simulated by mixing NG and $N_2$ at a ratio of 4:6. Liquid nitrogen was vaporized through a vaporizer with an electric heater to supply a large amount of $N_2$. Compressed natural gas (CNG) and compressed $CO_2$ were delivered to individual heat exchangers for temperature recovery after being passed through the corresponding regulators. A mass flow controller was installed in each gas supply line to adjust the gas flow, and a surge tank was used in order to absorb the pulsating effect from the engine as well as to merge all the gases. An air/fuel mixer was installed downstream of the surge tank for complete mixing with fresh air.

### 2.2. Experimental methods

The engine speed was fixed at 1800 rpm to supply 60 Hz AC electricity and the target power output was set to 60 kW for both the EGR and the lean burn engine operations. Engine lubrication oil and coolant were maintained at 90 and 80 °C by an external chilled-water cooling system, respectively. Spark ignition timing was swept in order to determine the MBT timing, but the test results were presented only at the MBT spark timings. Simulated