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A comparison between EGR and lean-burn strategies employed in a natural gas SI engine using a two-zone combustion model

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ABSTRACT

Exhaust gas recirculation (EGR) strategy has been recently employed in natural gas SI engines as an alternative to lean burn technique in order to satisfy the increasingly stringent emission standards. However, the effect of EGR on some of engine performance parameters compared to lean burn is not yet quite certain. In the current study, the effect of both EGR and lean burn on natural gas SI engine performance was compared at similar operating conditions. This was achieved numerically by developing a computer simulation of the four-stroke spark-ignition natural gas engine. A two-zone combustion model was developed to simulate the in-cylinder conditions during combustion. A kinetic model based on the extended Zeldovich mechanism was also developed in order to predict NO emission. The combustion model was validated using experimental data and a good agreement between the results was found. It was demonstrated that adding EGR to the stoichiometric inlet charge at constant inlet pressure of 130 kPa decreased power more rapidly than excess air; however, the power loss was recovered by increasing the inlet pressure from 130 kPa at zero dilution to 150 kPa at 20% EGR dilution. The engine fuel consumption increased by 10% when 20% EGR dilution was added at inlet pressure of 150 kPa compared to using 20% air dilution at 130 kPa. However, it was found that EGR dilution strategy is capable of producing extremely lower NO emission than lean burn technique. NO emission was reduced by about 70% when the inlet charge was diluted at a rate of 20% using EGR instead of excess air.

1. Introduction

Natural gas is one of the cleanest economically available fuels for internal combustion engines. Studies around the world have shown that engines running on natural gas emit significantly lower emissions compared to engines running on conventional fuels. For instance, Baldassari and coworkers [1] compared natural gas and diesel engine emissions, they showed that SI natural gas engine emissions of THC, NO_x, and PM were significantly lower than that of the diesel fueled engine with a reduction of 67%, 98%, and 96% respectively. Compared to gasoline engine emissions, another study showed that natural gas SI engines have the potential to achieve a reduction in CO, CO_2, NO_x, and non methane hydrocarbon emissions of 90–97%, 25%, 35–60%, and 50–75% respectively [2]. Catania and coworkers [3] showed that natural gas engine emissions have less impact on the global warming than gasoline emissions, taking the global warming potential of the methane into account, the authors concluded that the natural gas fueled engine showed a carbon dioxide equivalent reduction of 15–24% with respect to gasoline. In addition to its lower pollution impact, natural gas is available in many parts of the world that have poor oil reserves. Using natural gas as an alternative clean fuel will decrease the dependence on imported oil in these countries. Furthermore, the world reserves of natural gas are larger than the petroleum oil, thus the research in utilizing natural gas in engines represents an investment for the future. Recently, environmental and economical concerns have motivated many governments to expand in natural gas infrastructure in order to be feasible to passenger vehicles as well as stationary engines.

One of the natural gas engine combustion technologies, which begun in the early 1980s, is the "lean burn" combustion technique. This technology became dominant in gas engine industry as it led to high engine efficiency accompanied with longer durability and lower cost. Today after almost a quarter century of continuous lean burn engine development and investment, most of the conventional gas engines operate with lean burn mode. According to the Engine Manufacturers Association, USA 2004, over 80% of all heavy duty stationary natural gas engines sold in the USA employ lean burn combustion technology [4]. Most of the research conducted in the lean-burn strategy basically focused on extending the maximum burning lean limit in order to reduce NO_x emissions to satisfy the increasing emission restrictions. That usually was achieved by designing fast-burning combustion chambers and/or

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Nomenclature

B	cylinder bore, m
k	rate constant, m^3/kmol s
L	distance between cylinder head and piston, m
r_c	compression ratio
S_l	laminar flame speed, m/s
$\bar{S}_p$	mean piston speed, m/s
T	temperature, K
X_b	burned gas fraction
Z	mole fraction
$\Delta\theta$	combustion angle, rad
$\Delta\theta_b$	rapid burning angle, rad
$\Delta\theta_d$	flame development angle, rad
θ_o	crank angle at start of combustion, rad
v	kinematic viscosity, m^2/s

Subscripts

b	burned
u	unburned

Abbreviations

bsfc	brake specific fuel consumption
EGR	exhaust gas recirculation
MBT	maximum brake torque
PM	particulate matter
SCR	selective catalytic reduction
SI	spark ignition
THC	total hydrocarbon
TWC	three way catalyst
WOT	wide open throttle

employing the stratified charge concept, usually by using either a combustion pre-chamber or direct fuel injection. Recently, laser ignition systems have been developed in order to ignite extremely lean fuel air mixtures, which require high ignition energy.

Currently, increasingly stringent ambient air quality standards demand engine emissions to be extremely low; see Table 1 [5]. In order for the engine under the lean burn mode to produce lower NO_x emissions, it has to operate with a leaner mixture. In other words, the engine has to operate near the misfire limit to produce relatively lower NO_x emissions. As the engine operates near the misfire limit, the engine stability deteriorates, the hydrocarbon (HC) and CO emissions increase, and the engine efficiency decreases. Another way to control NO_x emissions is to retard the spark timing, which also leads to a decrease in engine efficiency and an increase in HC emissions. Therefore, it seems that any efforts towards a future decrease in NO_x emissions would lead to an increase in HC emission and a decrease in engine thermal efficiency. At the end, a compromise must be made between the increase in NO_x emissions and the decrease in engine efficiency. It has become obvious that it would be difficult for the conventional gas engine operating on lean burn mode to meet the stringent future emission standards especially for NO_x emissions without using exhaust gas after-treatment.

The current emission reduction technologies used for the NO_x emission after-treatment in lean burn engines such as the selective catalytic reduction (SCR) devices are expensive and add some complexity to the engine use. For example, the SCR technique consists of ammonia storage, feed, injection system and a catalyst. In this system, the ammonia is injected in the exhaust gases upstream of the catalyst. In order for this system to operate properly, a certain exhaust gas temperature range must be maintained [6]. In addition, an oxidation catalyst would also be necessary to reduce both the HC and CO emissions.

It could be concluded that in order for the engines to meet the future emission standards, some alternative techniques must be investigated and developed. One of these alternative techniques is the use of a three way catalyst (TWC) to reduce NO_x, HC, and CO emissions. The three way catalyst technology was developed in the 1970s for the automobile industry to reduce the gasoline engine emissions. The TWC is capable of reducing the three emissions at the same time and it is much less expensive than the SCR devices used in lean burn engines. However, in order for the TWC to operate efficiently, the engine must operate at near stoichiometric fuel–air ratio (i.e. without excess air). When the engine operates near the stoichiometric mixture, the in-cylinder temperature increases, and consequently, the thermal stresses and the knocking tendency increase. This would lead to some restrictions on the use of turbocharging, high compression ratio, and maximum brake torque (MBT) spark advance timing. As a result, the engine would operate less efficiently than a similar lean burn engine.

In order to reduce the in-cylinder temperature, an inlet charge dilution must be employed. One of the methods used to dilute the inlet charge is to recycle some of the exhaust gases back into the cylinder intake with the inlet mixture. This method is called exhaust gas recirculation (EGR). Using EGR with the stoichiometric inlet mixture will lead to a decrease in the in-cylinder temperature and a decrease in knocking tendency and could permit the engine to use turbocharging, relatively higher compression ratio, and MBT spark advance timing to achieve a relatively higher thermal efficiency compared to non diluted stoichiometric mixture operation. In addition, adding EGR to the inlet mixture will reduce the oxygen partial pressure in the inlet mixture, and consequently the in-cylinder NO_x production will decrease. Furthermore, as EGR will be added to a stoichiometric mixture, the use of a TWC for necessary emission reductions is also possible.

Although the use of EGR with a TWC technique is expected to economically produce lower emissions than lean-burn strategy, the effect of using EGR compared to lean burn on some of engine performance parameters such as engine fuel consumption is still not quite certain. Some conflicting results were found in the literature review regarding to this issue. For instance, Corbo and coworkers [7] converted a heavy duty turbocharged diesel engine to work on natural gas fuel. They employed both lean burn and stoichiometric mixture with EGR and a TWC approaches after conversion and compared the engine performance and emissions for both cases. The authors concluded that the use of both EGR and lean burn techniques led to a similar maximum thermal efficiency of 34%. Nellen and Boulouchos [8] used a stoichiometric mixture with cooled EGR and a TWC in a turbocharged natural gas SI engine used for cogeneration applications. The authors aimed to achieve low emissions and high efficiency by using this concept. The authors optimized the same engine for lean burn operation with an oxidation catalyst. They concluded that the EGR concept resulted in a more superior engine performance and emissions compared to the lean burn technique. The engine achieved a thermal

Table 1
Emission standards, g/kW h [5].

Year	Standard	CO	HC	NO_x	PM
1996	Euro2	4	1.1	7	0.15
2000	Euro3	2.1	0.66	5	0.1
2005	Euro4	1.5	0.46	3.5	0.02
2008	Euro5	1.5	0.46	2	0.02