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Combustion and emission characteristics of a natural gas-fueled diesel engine with EGR

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ABSTRACT

The use of natural gas as a partial supplement for liquid diesel fuel is a very promising solution for reducing pollutant emissions, particularly nitrogen oxides (NOx) and particulate matters (PM), from conventional diesel engines. In most applications of this technique, natural gas is inducted or injected in the intake manifold to mix uniformly with air, and the homogenous natural gas–air mixture is then introduced to the cylinder as a result of the engine suction.

This type of engines, referred to as dual-fuel engines, suffers from lower thermal efficiency and higher carbon monoxide (CO) and unburned hydrocarbon (HC) emissions; particularly at part load. The use of exhaust gas recirculation (EGR) is expected to partially resolve these problems and to provide further reduction in NOx emission as well.

In the present experimental study, a single-cylinder direct injection (DI) diesel engine has been properly modified to run on dual-fuel mode with natural gas as a main fuel and diesel fuel as a pilot, with the ability to employ variable amounts of EGR. Comparative results are given for various operating modes; conventional diesel mode, dual-fuel mode without EGR, and dual-fuel mode with variable amounts of EGR, at different operating conditions; revealing the effect of utilization of EGR on combustion process and exhaust emission characteristics of a pilot ignited natural gas diesel engine.

1. Introduction

With the increasing concern regarding diesel engines emissions, including NOx, smoke, and PM, and the rising cost of the liquid diesel fuel as well, the utilization of alternative fuels in diesel engines seems to present attractive solution for both environmental and economical problems.

Among the alternative fuels, natural gas is very promising and highly attractive. Beside its availability in several areas worldwide at encouraging prices, natural gas is eco-friendly fuel that has clean nature of combustion. It can substantially reduce the NOx emissions by approximately 50–80% while produces almost zero smoke and PM; which is extremely difficult to achieve in DI diesel engines. It can also contribute to the reduction of carbon dioxide (CO_2) emissions, due to the low carbon-to-hydrogen ratio. In addition, natural gas has a high octane number, and hence high autoignition temperature. Therefore, it is suitable for engines with relatively high compression ratio without experiencing the knock phenomenon. Moreover, it mixes uniformly with air, resulting in efficient combustion to such an extent that it can yield a high thermal efficiency comparable to the diesel version at higher loads [1–3].

The most common natural gas–diesel operating mode is referred to as the pilot ignited natural gas diesel engine; where most of the engine power output is provided by the gaseous fuel, while a pilot amount of the liquid diesel fuel, represents around 20% of the total fuel supplied to the engine at full load operation (energy basis), is injected near the end of the compression stroke to act as an ignition source of the gaseous fuel–air mixture. The injected spray ignites several points in the gaseous fuel–air mixture, forming multi flame-fronts that travel throughout the entire mixture. The engine power output is controlled by changing the amount of the primary gaseous fuel, while the pilot fuel quantity is kept constant [4–6].

In some applications, natural gas is directly injected into the cylinder shortly before the end of the compression stroke. This technique provides better fuel economy and more efficient combustion, and maintains the power output and the thermal efficiency of an equivalently-sized conventional diesel engine [7,8]. However, direct injection of natural gas requires the development of special high-pressure gaseous injectors. Therefore, in most applications to date, natural gas is inducted or injected in the intake manifold to mix uniformly with air, and the homogenous natural gas–air mixture is then introduced to the cylinder as a result of

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Nomenclature

Latin

C_p	specific heat at constant pressure (J/kg k)
C_v	specific heat at constant volume (J/kg k)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/h)
p	in-cylinder pressure (N/m^2)
Q	heat (J)
V	cylinder volume (m^3)

Greek

γ	specific heat ratio (–)
θ	crank angle (°)
ϕ	equivalence ratio (–)

Superscripts

stoic	stoichiometric

Subscripts

D	diesel
i	intake
NG	natural gas
tot	total

Abbreviations

ABDC	after bottom dead center
A/D	analog-to-digital
AFR	air to fuel ratio (kg air/kg fuel)
ATDC	after top dead center
BBDC	before bottom dead center
BTDC	before top dead center
CA	crank angle
CAD	crank angle degree
CI	compression ignition
C/H	carbon to hydrogen ratio
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variance
DI	direct injection
EGR	exhaust gas recirculation
EI	emission index
HC	unburned hydrocarbon
HHR	heat release rate (J/CAD)
NDIR	non-dispersive infrared
NO	nitric oxide
NO_2	nitrogen dioxide
NOx	nitrogen oxides
PC	personal computer
PM	particulate matters
ROPR	rate of pressure rise (bar/CAD)
TDC	top dead center

the engine suction. A typical four-stroke engine has one suction stroke per cycle while there is no suction in the other three stokes. For that reason, the measurement of the gaseous fuel flowrate becomes a point of doubt and should be emphasized and carefully treated, in order to avoid the use of inappropriate measurement technique that does not take into account that the actual gaseous fuel consumption takes place in only one stroke per cycle; i.e. the suction stroke. As the gaseous fuel should be inducted into the cylinder as a result of the engine suction only, its pressure should be kept as low as possible to prevent the flow while there is no suction. Some flowrate measuring instruments, such as rotary flowmeters and variable area flowmeters, involve a considerable pressure drop, and therefore they require the increase of gas pressure in order to overcome this pressure drop. The increase of gas pressure may lead to continuous gas supply during the four strokes while the actual consumption takes place in only one stroke. In such a case, the measured value would not represent the actual consumption. Hence, these instruments cannot be used in measuring the gaseous fuel flowrate in reciprocating internal combustion engines.

During the last years, the implementation of pilot ignited natural gas diesel engines has been investigated, experimentally and theoretically, by numerous researchers. Combustion and exhaust emission characteristics of this type of engines have been examined in various studies [9–13]. Several predictive models have also been developed in order to provide better understanding of the combustion process in gas–diesel engines and some of their performance features and emission characteristics [14–16]. Moreover, the effects of some important parameters, such as pilot diesel fuel quantity, pilot injection timing, natural gas percentage, natural gas composition, and intake air temperature have also been studied [17–21].

It has been reported that the main drawback of this operating mode, in contrast with conventional diesel mode, is the negative effect on engine efficiency, CO and HC emissions, particularly at low and intermediate loads. At high load, the improvement in gaseous fuel utilization leads to corresponding improvement in both engine performance and CO emissions, and the thermal efficiency becomes comparable to that observed under conventional diesel operation. Alternating some engine parameters, such as the increase of pilot fuel quantity and the advance of injection timing, has positive effect on engine performance, CO and HC emissions, but it adversely affects NOx emission.

In order to overcome these drawbacks while provide further reduction in NOx emission at the same time, EGR may be used. By employing EGR, portion of the unburned gas in the exhaust from the previous cycle is recirculated, and expected to possibly reburn in the succeeding cycle; resulting in a reduction in the unburned fuel with simultaneous improvement in thermal efficiency and reduction in CO. Furthermore, the application of EGR involves replacement of some of the inlet air with EGR. The consequences of this replacement include a dilution of the inlet charge and an increase in its heat capacity. These two effects lower the combustion temperature. The simultaneous reductions of oxygen concentration, combustion temperature, and flame propagation speed reduce NOx substantially. However, as NOx is reduced, PM is increased; due to the lowered oxygen concentration. When EGR further increases, the engine operation reaches zones with higher instabilities, increased carbonaceous emissions, and even power losses. [22–25].

The aim of the present work is to investigate, experimentally, the potentials of the use of EGR in pilot ignited natural gas diesel engines. A complete set of measurements is conducted for various engine operating mode; diesel, plain dual-fuel (without EGR), and dual-fuel with EGR, at different operating conditions. Detailed results are given for combustion characteristics, engine performance, and exhaust emission analysis.

2. Experimental apparatus and conditions

2.1. Experimental apparatus

The present study has been conducted on a Petter PH1W single cylinder, naturally aspirated, four-stroke, water cooled, high speed,