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A combined experimental and theoretical study of diesel fuel injection timing and gaseous fuel/diesel mass ratio effects on the performance and emissions of natural gas-diesel HDDI engine operating at various loads

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HIGHLIGHTS

- Experiments and two-zone modeling studies in natural gas/diesel HDDI engine.
- Increasing methane concentration increases ISEC, CO and max pressure.
- Increasing methane concentration reduces NO and soot.
- Advancing diesel fuel injection timing reduces ISEC, CO and soot.
- Advancing diesel fuel injection timing increases max pressure and NO.

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ABSTRACT

Diesel engines find widespread applications in stationary and transportation systems owing to their high fuel efficiency, high torque output, and great size flexibility. However, they still constitute major polluting sources, especially regarding NO and particulate emissions. Therefore, more conventional diesel engines internationally are pursuing the option of conversion to using natural gas as a supplement fuel for the conventional diesel fuel. Many research studies carried out in the aforementioned research field have shown that the specific engine operating mode, in comparison to the conventional diesel one, suffers from higher specific fuel consumption and CO emission. The diesel fuel injection timing and the proportion of the gaseous fuel influence significantly the combustion mechanism, with this effect becoming more evident at part load conditions. Thus, in order to examine the effect of these two parameters on the performance and exhaust emissions, a combined experimental and theoretical investigation is conducted herein on a single-cylinder research, dual fuel (diesel-natural gas), HDDI compression ignition engine. Specifically, through the experimental investigation the effect of diesel fuel injection timing is examined on the performance and exhaust emissions of the engine operating under part load and constant natural gas/diesel mass ratio conditions. Moreover, following validation of the latter, theoretical results concerning the combined effects of both parameters of diesel fuel injection timing and natural gas/diesel mass ratio on the performance and exhaust emissions characteristics of the engine operating at two different loading conditions are obtained, via the application of an in-house, comprehensive, two-zone phenomenological model. The main objective of this assessment is to record and comparatively evaluate the relative impact of these parameters for part and high engine loading conditions. From the experimental and theoretical findings, it is revealed that for the examined test engine operating under constant natural gas/diesel mass ratio, a restricted increase in the diesel fuel injection timing could be a promising solution for engine efficiency improvement and CO emission mitigation, while simultaneously it seemed to increase NO emissions. For extremely advanced diesel fuel injection timing, a simultaneous variation of natural gas/diesel mass ratio at both engine loading conditions could cause problems to the engine structure because, in those cases, the maximum cylinder pressure becomes considerable and hence possibly harmful to the engine structural integrity. The information derived from the present

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Nomenclature

$\dot{m}$	mass flow rate (kg/s)
x	diesel fuel supplementary ratio (%)
φ	total fuel to air excess ratio

Subscripts

d	diesel
g	gaseous fuel
st	stoichiometric
tot	total

Abbreviations

AFR	air-fuel ratio (by mass) (kg/kg)
CA	crank angle
CI	compression ignition
CO	carbon monoxide emission
DIT	diesel fuel injection timing (deg CA)
FSN	Filter Smoke Number
HC	unburned hydrocarbons emission
HDDI	heavy duty direct injection
IMEP	indicated mean effective pressure (bar)
ISEC	indicated specific energy consumption (MJ/kWh)
LHV	lower heating value (kJ/kg)
NO	nitric oxide emission
PES	percentage of the released total heat (energy) substituted by gaseous fuel (%)
ROHR	rate of heat release rate (J/deg CA)
rpm	revolutions per minute
SCRE	single cylinder research engine
TDC	top dead center

work is valuable, especially if one wishes to define the optimum combination of examined strategies for improving the behavior of an existing engine running under natural gas/diesel operating mode.

1. Introduction

The energy policy, whether in developing or industrialized countries, is an issue frequently discussed under economic, technical, and political perspectives. It has become common belief that today's main resources of energy, such as the conventional petroleum based liquid fuels, will become scarce within the next generation [1–6]. Awareness of limitations of fossil fuels reserves and the fact that burning of fossil fuels has a major contribution to the greenhouse gas emissions, has led to a growing interest in the use of alternative energy resources (alternative fuels) for the operation of compression ignition (CI) internal combustion engines that are one of the main energy consumers [7–12].

Moreover, one of the main objectives for improving the combustion process of conventional CI engines is to find effective ways to reduce exhaust emissions, without making serious modifications on their mechanical structure. Various solutions have been proposed, and among those the use of natural gas as a supplement for the conventional liquid diesel fuel (i.e. natural gas-diesel dual fuel CI engine) possesses a dominant place, owing to its inherent clean nature of combustion (low cetane index and low evaporation temperature) [13–18], combined with the widespread availability at attractive prices. Moreover, natural gas can be used safely in compression ignition environment since its auto-ignition temperature is higher compared to that of conventional liquid diesel fuel, while the use of natural gas as a supplement to conventional diesel fuel has proved to be an effective way for improving the soot/NOx trade-off without making significant modifications on the engine mechanical structure [19–21].

Thus, many conventional diesel engines can also operate on the dual fuel (natural gas-diesel) principle, where a portion of the energy released inside the engine cylinder comes from the combustion of the gaseous fuel, while the rest from the combustion of the liquid diesel fuel, without serious modifications. The majority of this type of engines (i.e. dual fuel CI engines) operates as "Fumigated Dual Fuel CI Engines", where the natural gas at low pressure is fumigated into the intake air during the induction stroke (i.e. Low-Pressure Dual Fuel Compression Ignition Engines). In this type of dual fuel engines, the air supply to the engine is not throttled and the amount of the fumigated natural gas replaces an equal amount of the inducted combustion air. Moreover, a homogeneous natural gas–air mixture is compressed rapidly below its auto-ignition condition and is ignited by the injection of an amount of liquid diesel fuel around top dead center, while the desired engine power output is controlled only by changing the amount of natural gas [13,22–25].

To optimize engine performance and emissions in dual fuel engines solely by experimental means can be very expensive and time-consuming. A mathematical model could provide a fast and inexpensive way for describing details of the complicated mixing, combustion, and pollutants formation processes. The need for accurate predictions of emitted pollutants has forced researchers to develop multi-zone phenomenological [20,26–28] and also multi-dimensional [29] models, which are useful solutions for examining problems characterized by the need for detailed spatial information and complex interactions of many phenomena simultaneously, but are limited by computer size and cost of operation. Thus, for the present study, a two-zone simulation model [20] was chosen, where the effect of changes in engine design and operation are fairly well approximated by phenomenological modeling of the various mechanisms involved. This model also has the advantages of relative simplicity and reasonable computational time.

A substantial research (experimental and theoretical) on fumigated dual fuel compression ignition engines has concentrated on the extent of dual-fuelling and its effect on emissions and performance in [30–35]. The fumigated natural gas combustion in compression ignition environment, compared to the conventional diesel operation, is found to be an effective way in the simultaneous reduction of nitric oxide emission and particulate matter as well, but it suffers from high unburned hydrocarbon (HC) and carbon monoxide (CO) emissions and also from poor performance.

According to many research works, alterations in various critical engine parameters, such as the diesel fuel injection timing [36–40] and the percentage of the total fuel chemical energy input substituted by natural gas [41–46], may be used to improve the engine efficiency and to restrain the increase of CO and HC emitted from a fumigated dual fuel compression ignition engine, when it operates at various engine loading conditions [47–50]. Thus, at