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# Theoretical study of the effects of engine parameters on performance and emissions of a pilot ignited natural gas diesel engine ☆

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ABSTRACT

With the increasing concern regarding diesel vehicle emissions and the rising cost of the liquid diesel fuel as well, more conventional diesel engines internationally are pursuing the option of converting to use natural gas as a supplement for the conventional diesel fuel (dual fuel natural gas/diesel engines). The most common natural gas/diesel operating mode is referred to as the pilot ignited natural gas diesel engine (PINGDE) where most of the engine power output is provided by the gaseous fuel while a pilot amount of the liquid diesel fuel injected near the end of the compression stroke is used only as an ignition source of the gaseous fuel–air mixture. The specific engine operating mode, in comparison with conventional diesel fuel operation, suffers from low brake engine efficiency and high carbon monoxide (CO) emissions. In order to be examined the effect of increased air inlet temperature combined with increased pilot fuel quantity on performance and exhaust emissions of a PINGD engine, a theoretical investigation has been conducted by applying a comprehensive two-zone phenomenological model on a high-speed, pilot ignited, natural gas diesel engine located at the authors' laboratory. The main objectives of the present work are to record the variation of the relative impact each one of the above mentioned parameters has on performance and exhaust emissions and also to reveal the advantages and disadvantages each one of the proposed method. It becomes more necessary at high engine load conditions where the simultaneous increase of the specific engine parameters may lead to undesirable results with nitric oxide emissions.

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## 1. Introduction

One of the main objectives for improving the combustion process of conventional internal combustion 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 them the use of gaseous fuels posses a dominant place [1–4]. A good choice is the use of natural gas as a supplement for the conventional diesel fuel (dual fuel natural gas diesel engines), owing to its inherent clean nature of combustion combined with the high availability at attractive prices. Furthermore, due to its relatively high auto-ignition temperature natural gas is suitable for engines with relatively high compression ratio (i.e., compression ignition engines).

Thus, many conventional compression ignition engines can also operate on dual fuel principle (i.e., natural gas and diesel fuel). For the majority of the compression ignition engines, natural gas is most usually inducted with the air during the induction stroke. At the same point near the top dead centre (TDC) a pilot amount of the liquid diesel fuel, which represents less than 20% of the total energy released at full engine load operation, is injected through the conventional diesel fuel injection system. The amount of the liquid fuel injected acts as an ignition source for the compressed gaseous fuel/air mixture. The specific type of dual fuel engine is referred to as "pilot ignited natural gas diesel engine – PINGD" where its power output is controlled only by changing the amount of the primary gaseous fuel. In PINGD engine the air supply is not throttled while

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**Nomenclature**

| | |
|---|---|
| $\dot{m}_{mix}$ | Mass flow rate of the air–gaseous fuel mixture at inlet valve closure (kg/h) |
| $\dot{m}_{NG}$ | Natural gas consumption rate, [kg/h] |
| $\dot{m}_{D}$ | Diesel fuel consumption rate, [kg/h] |
| $T$ | Temperature, [K] |

*Greek letters*

| | |
|---|---|
| $\lambda$ | Total air excess ratio, [–] |

*Abbreviations*

| | |
|---|---|
| AFR | air to fuel ratio (by mass) |
| B | Before |
| BDC | Bottom dead centre |
| BTDC | Before top dead centre |
| BSFC | Brake specific fuel consumption |
| °CA | Degrees of crank angle |
| CO | Carbon monoxide |
| D | Diesel |
| DI | Direct injection |
| deg | Degrees of crank angle |
| NDO | Normal diesel operation |
| NG | Natural gas |
| NPFQ | Normal pilot fuel quantity |
| NO | Nitric oxide |
| PFQ | Pilot fuel quantity |
| PIDFO | Pilot ignited dual fuel operation |
| ppm | Parts per million (by volume) |
| rpm | Revolutions per minute |
| TDC | Top dead centre |

the engine power output is controlled by changing the amount of the primary gaseous fuel (i.e., natural gas) [5,6]. Moreover, when engine operates at constant engine speed, the change in the amount of the gaseous fuel results in a change in the amount of the inducted combustion air since the total amount of the inducted mixture (i.e., gaseous fuel and air) is kept constant. Most current dual fuel engines are made to operate either on dual fuel principle with diesel ignition, or simply as conventional diesel engines [5,6].

Many research studies [5–22] have reported that, the main drawback of pilot ignited natural gas/diesel engine operation in contrast with conventional diesel operation, is the negative effect on engine efficiency, carbon monoxide (CO) and unburned hydrocarbon (HC) emissions, especially at low and intermediate load operating points. At high load, the improvement of gaseous fuel utilization leads to a relevant improvement of both engine performance and carbon monoxide emissions, but their values continue to be inferior to the respective values observed under normal diesel operation. During the last few years, the present research group has also reported experimental investigations along with computer simulations conducted on such kind of engines [23–27].

According to prior studies [10–27], alterations in various engine operating parameters, such as pilot fuel quantity, pilot diesel fuel injection timing and air inlet preheating, may be used to improve the engine efficiency and to restrain the increase of CO and HC emitted from a compression ignition engine running under pilot ignited natural gas diesel operating mode.

The primary objective of the present work is to examine, on a theoretical basis, the effect of air inlet preheating in combination with the pilot fuel quantity on engine performance characteristics, soot, NO (nitric oxide) and CO emissions of a single cylinder, high-speed, direct injection diesel engine, which has been modified to operate under pilot ignited dual fuel mode. The evaluation of the calculations revealed the applicability of each technique on an existing DI diesel engine operating under dual fuel mode. The theoretical results have been produced using a two-zone phenomenological combustion model, which predicts in-cylinder pressure and heat release rate histories as well as soot, NO and CO concentration profiles. The model has been properly modified to describe the combustion process that takes place in pilot ignited natural gas diesel engines. Model predictions have been already presented in the past by the present research group [23–27]. Theoretical results are validated against experimental values, which were obtained at various speeds and loads from a single cylinder DI diesel engine operating under dual fuel mode at fixed pilot fuel quantity and normal injection advance without air inlet preheating (normal pilot ignited dual fuel operation – NPDFO). Moreover, model predictions are contrasted with additional experimental results obtained from the literature [5–22,28,29] to ensure that the two-zone model predicts with reasonable accuracy the effect of pilot fuel quantity and air inlet preheating on engine performance characteristics, soot, NO and CO emissions. This comparison revealed that the developed model captures more in a qualitative rather than in quantitative manner the influence of pilot fuel quantity and intake air preheating on engine performance and exhaust emissions. Hence, the two-zone combustion model can be used to examine the effect of both parameters on engine performance and pollutant emissions.

From the theoretical findings, important information is derived revealing the effect of each strategy on engine performance and pollutant emissions. This is accomplished through the comparison of the calculated maximum combustion pressure and total brake specific fuel consumption for both possible strategies, at low and high loads and for the same engine speed. Furthermore, each one of the proposed strategies is evaluated concerning the effect of both parameters (i.e., pilot fuel quantity and air inlet preheating) on the formation of pollutant emissions, by comparing the related values to the corresponding ones obtained under normal pilot ignited dual fuel operation (i.e., NPDFO) and normal diesel operation (i.e., NDO). This information is extremely valuable, if one wishes to decide on the proper strategy to improve the behavior of an existing direct injection diesel engine operating under pilot ignited dual fuel operating mode.

## 2. Model description

In the present work only an outline of the model is given, on the one hand because of the lack of space and on the other because this is based on an existing model that has been presented in detail in previous publications by the authors [22–27]. As stated above, the main purpose of this work is the theoretical study, which is to be conducted via the simulation model, concerning the effect of pilot diesel fuel quantity and injection timing on both engine performance and emissions. The model used is a phenomenological two-zone one, examining the closed part of the engine cycle. The cylinder charge during the compression phase is treated as a single zone (unburned zone), with assumed uniformity in space of pressure, temperature and composition. During the compression phase, the cylinder charge is compressed to a high pressure and temperature as TDC is approached. Prior to reaching TDC, a small amount of diesel fuel is injected into the combustion chamber, which

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