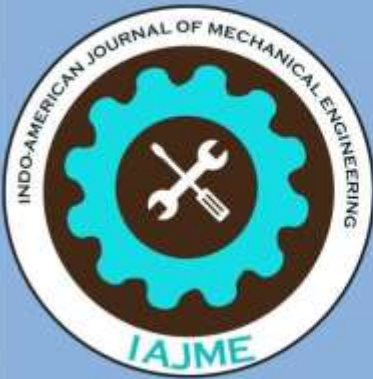




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Analysis of a Two-Fuel Diesel Engine Numerically and Experimentally

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Abstract

This research examines the impact of varying fuel ratios on the efficiency and emissions of a common rail diesel engine fed both natural gas and diesel oil. In a dual-fuel engine, the diesel pilot injection ignites the NG/air mixture pre-mixed at the intake port. The dual-fuel system was analyzed using both computational and experimental methods. The work on a diesel engine presented here is an attempt to gauge how well CFD can anticipate the key aspects of that engine's functioning. Validating such potential and simultaneously drawing attention to the most pressing issues that occur from real engine running with varying NG / diesel oil fuel ratios are two goals of the experimental research.

1. Introduction

The use of natural gas as a supplement to diesel fuel is central to the dual-fuel (diesel/NG) idea, which offers a practical means of lowering diesel emissions. If you're concerned about the emissions from a diesel engine, namely nitrogen oxides (NO_x) and particulate matter (PM), this may be a viable option to "clean" the exhaust. In particular, the most effective outcomes might include achieved if the engine has an exhaust gas recirculation (EGR) system; in fact, it is well known [1-3] that the contribution of the inert substances in the oxidant is necessary for the development of a smoother combustion process within a regime known as homogenous combustion. In order to initiate combustion in a port premixed NG/air mixture, the dual fuel operation makes use of

a diesel pilot injection. Under ideal conditions, natural gas (NG) can be used in place of up to 90% diesel oil. At full power, heavy knocking can damage the engine, and idle and low loads are where poor combustion quality and high HC emissions typically occur. The efficiency of a diesel engine may be approached with this technique, with the added bonus of significantly reduced global pollution emissions. As the fossil fuel with the lowest C/H ratio, methane is also expected to produce the fewest greenhouse gas emissions. Many researchers [4-11] have looked into the dual-fuel combustion system in recent years, but it has not yet achieved widespread adoption because of its higher HC and CO emissions than a conventional diesel engine, particularly at low loads.

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Binary fuel blends, in which two fuels with differing auto ignition properties are used to improve HCCI Engine combustion timing management, are proposed by the authors in [3]. The available chemical kinetic processes for n-heptanes and natural gas are optimized. Using 3D-CFD models coupled with chemical kinetics, Maghbouli et al. [5] demonstrate the results of a numerical study of the combustion and emission characteristics of dual-fuel engines, and the authors of [7] examine the performance of dual engines powered by fuels of varying LPG composition using a single cylinder. This work intends to evaluate the CFD ability to anticipate the major aspects of this engine type's operation via a combined numerical - experimental analysis of dual-fuel diesel engines. The experimental studies are a useful tool for verifying such a potential and, at the same time, drawing attention to the most pressing issues that come from running the engine with varying concentrations of diesel fuel and natural gas. Fluid dynamic simulations are highly helpful in putting into evidence the important processes that occur during the dual-combustion, such as the usual flame propagation across the premixed methane-air medium that is initiated by the early self-ignition of the diesel fuel.

2. Experimental study and results

In addition to delivering excellent signals on the dual-fuel working engine, the experimental data have been utilized to both build up and evaluate the numerical model. The testing was performed at InstituteMotor (CNR) using a turbocharged diesel engine with a 1.9 liter capacity and common rail direct injection (Table 1).

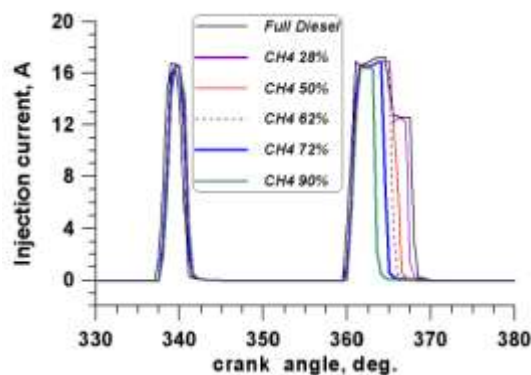


Figure 1. Diesel injector command signal varying CH4 ratio

Table 1. Engine main characteristics for experimental tests

Engine	1.9 Multijet
Type	4 stroke
Number of cylinders	4
Valves /cyl.	2
Bore (mm)	82
Stroke (mm)	90.4
Compression Ratio	19:1

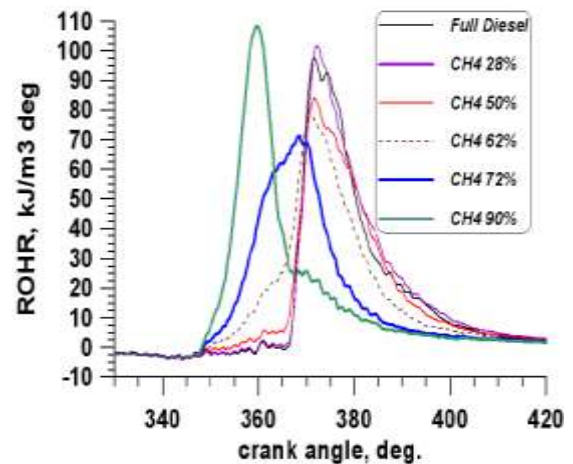


Figure 2. Experimental Rate of Heat Releases by varying the NG ratio

Table 2. NG composition and its main characteristics

Fuel properties	Basic data
α_{st}	15.73
ρ (kg/Stdm ³)	0.83
LHV(MJ/kg)	45.83
CH ₄ (%vol)	85.44
Ethane (%vol)	8.38
Propane (%vol)	1.71
Buthane (%vol)	0.47

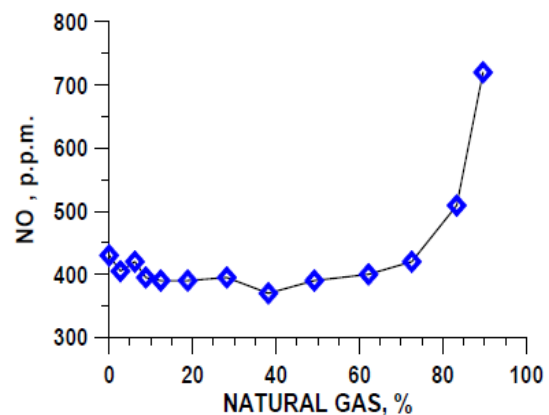
The engine is capable of running on either diesel fuel (FD) or a combination of diesel and gasoline (DF). In the latter situation, a pilot diesel injection ignites a combination of natural gas and air. The primary features of the NG used in the experiments are shown in Table 2. When running in DF mode, the engine has no external hardware requirements. This allows for a smooth transition from FD to DF operation. In DF mode, a pilot diesel injection is used to ignite the primary fuel (NG) together with air in the intake manifold, same as in a conventional diesel engine. Therefore, there are numerous front flames that can interact with one another, resulting in a combustion process that is similar to that of a SI engine but with the added complexity of multiple ignition points. Therefore, DF operation can give rise to a wide variety of combustion phenomena. The sweet spot for operation is usually found around in the middle range of load/speed, with low and high load posing the greatest challenges. At low load, the mixture becomes too lean, and the ignition limits are not reached, because the mixture is homogeneous and the diesel engine does not have a throttle valve to control the torque output. As a result, an NG/air combination will not support the development of a frontal flame.

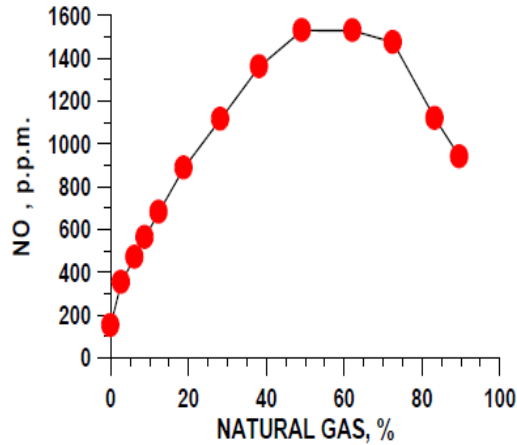
THC emissions are high and efficiency is poor under these circumstances. At high power output, however, combustion conditions improve significantly; however, because each diesel injector hole has at least one ignition start point, the combustion speed can increase to the point where knocking is induced, despite the high methane octane number (130). This tendency makes it harder to regulate DF combustion efficiently. However, it can be equally challenging to establish a trustworthy numerical model. The electrical signal that controls the injectors' functioning is included in the experimental data in order to enhance the modeling capabilities of the

numerical tool created at University of Napoli Federico II. Such information has been used primarily in this endeavor to pinpoint the precise times of pilot and main injection activation. As a consequence, we should be able to better match the engine's performance with the model findings thanks to more precise heat-release calculations. Diesel oil quantities ranging from FD to DF and up to their maximums were evaluated under a specific engine condition (i.e. 2000 rpm/100 Nm). Natural gas can replace 90% of diesel fuel. For each experimental operating state, the injection time is shown in Table 3. Figure 1 depicts the electrical signals of a diesel injector at various test sites. Because of these tendencies, it was possible to estimate the total volume of diesel injected during both the pilot and main injection phases. In particular, a comparison of the pilot and main command signals in DF state at NG max (90%) reveals striking similarities, suggesting that comparable amounts of diesel injection might be anticipated. It has been assumed that the pilot quantity is precisely half of the total, or 1 mg/cycle, as the total diesel oil in this scenario is 2 mg/cycle (as experimentally observed).

Table 3. Changable crank angle at start of engine through pilot and main injection using CH₄ ratio

Test case	Pilot		Main		Fuel (mg/cycle)
	SOI (ca)	EOI (ca)	SOI (ca)	EOI (ca)	
Fulldiesel	341.5	345	302.5	375.5	20.791
CH ₄ =0%	341.5	345.5	302.5	375.5	19.590
CH ₄ =0%	341.5	345.5	302.5	375.5	19.291
CH ₄ =0%	338	345.5	302.5	375.5	18.157
CH ₄ =10%	338	345.5	303	375.5	17.886
CH ₄ =10%	341	345.5	302.5	372	16.431
CH ₄ =20%	341	345.5	302.5	372	14.551
CH ₄ =30%	341	345.5	302.5	374.5	12.134
CH ₄ =50%	341	345.5	303	374	9.850
CH ₄ =60%	341	345.5	303	373.5	7.044
CH ₄ =70%	341	345.5	302.5	372.5	4.582
CH ₄ =80%	341	345.5	302.5	371.5	2.271
CH ₄ =90%	341	345.5	302.5	371.5	1.088





Mass fractions of polluting species as measured in experiments

All experimental sites have been kept under the identical circumstances, with only the primary injection period and, by extension, the injected mass of diesel oil, changing. The failure to amend the pilot legislation in particular that neither the amount of advance nor the diesel oil injection changes during the pilot phase. Neither the turbine configuration nor the trapped air mass changed much. To ensure that the engine performance level (load = 100 Nm and speed = 2000 rpm) was not dramatically altered throughout the testing, only the diesel oil amount during the main injection was lowered and replaced with a matching quantity of natural gas. For a clearer picture of how changes in the natural gas ratio affect the rate of heat release, see Figure 2. When CH₄ is 90%, the natural gas ignition process is expected to begin on a steep slope, producing more NO_x and less CO (Figure 3). Figure 4 depicts the effect of changing the CH₄ ratio on the in-cylinder pressure cycles.

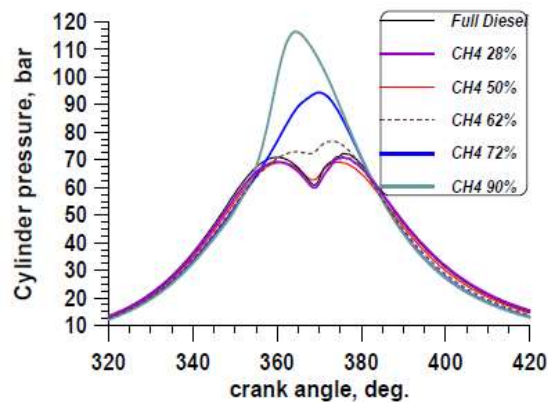


Figure 4. Experimental pressure cycles at different CH₄ rates

Table 4. Engine Characteristics for numerical calculations

Engine	3.0 Multijet
Type	4 stroke C.I.
	Common Rail
Number of cylinders	6
Valves /cyl.	4
Bore (mm)	84
Stroke (mm)	90
Cylinder vol. displ. (cm ³)	499
Compression ratio	17:6

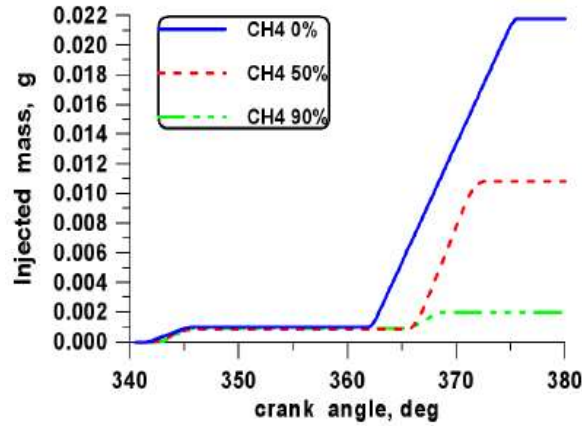
3. Numerical study and results

To investigate the in-cylinder dual/fuel combustion process from experimental data and to discover the main characteristics of this new technology in terms of performance, computational activities aiming at simulation of the in-cylinder phenomena have been carried out using the solver KIVA-3V [12]. CFD based estimates for complete diesel operation under a wide range of situations were validated by referring to known experimental data for a four-stroke, common-rail, turbocharged diesel engine with potential external EGR (Table 4). The main fuel (NG) is mixed with air before being delivered into the cylinder, and the NG/air combination is then ignited by a pilot diesel injection. In order to achieve more consistent combustion as the diesel content decreases, the injection law must be modified to accommodate the dual/fuel solution. These modifications begin with the experimental split-injection laws defined by the manufacturer of the engine control system and progress to the progressive variation of the duration of the main injection. All fuel injection timings were set so that auto-ignition occurred at roughly the same crank angle. Figure 1 displays the fuel injection profile in terms of injection current, whereas Figure 5 displays the injected fuel mass computed for each calculation to guarantee conformity with the experimental mass/cycle data (Table 3). Including the intake and exhaust ducts and valves, as shown in Figure 6, is the whole computational domain. The ICEM meshing tool was used to create the cylindrical and duct-structured mesh. Using the mesh generation consistent with the valve geometry, as reported in previous works [11,13], a multi-block structured Cartesian grid has been established (the grid size independence was

reached after with a mesh of 104000 cells, the cylinder and bowl volume discretizations being of nearly 58000 and 5000 cells respectively). Also thanks to the well-known robustness of the KIVA3-V solver, the development of multiple numerical cases was possible in a reasonable amount of computational time, despite the reduced mesh size producing a fair convergence of the results when compared with those obtained with more refined grids.

Thermo chemical characteristics of methanol-and-natural-gasoline mixtures (Table 5)

CH ₄ %	α_{st}	f_{st}	T _{0f} [K]	LHV [MJ/kg]
0	14.92	.0670	2311	42.00
28	15.54	.0643	2290	44.23
50	16.02	.0624	2266	46.00
72	16.51	.0605	2237	47.76
90	16.91	.0591	2228	49.20



Mass profiles of diesel oil and injected fuel

The CFD calculations are summarized in Table 7. Nearly the same in-cylinder mean effective pressure is reached regardless of NG rate, but a slight decrease is seen with increasing NG rates, leading to a corresponding decay. By reducing heat loss. On the other hand, when the dual fuel operation is activated, the exhaust temperature rises steadily, necessitating a different reaction from the turbo charging system. As predicted, the CO₂ contents drop with increasing CH₄ rate; more interesting is the continual lowering of the specific CO₂ index, which demonstrates more convincingly the advantages of adopting the dual-fuel idea. The most important pressure cycles from the

various numerical test situations are shown in Figure 7. The numerical periodic convergence is shown in this and the next figures, which are based on the results of the third cycle of computation. The initial no-NG (FD) instance is shown by the solid black line, which occurs when the engine is operating in full diesel mode. The form of the pressure cycles and the location and magnitude of the peak pressures shift when the methane rate is increased owing to a distinct combustion development. Figure 8 shows a trend in fuel consumption that reflects the varying rates of heat release from the various NG-diesel combinations. As the methane content rises to 90%, higher flame speeds occur in the methane/air mixture, which explains the quicker vapour decrease for this extreme case. Figure 9 displays the stated average temperature trends; the higher the levels, the greater the methane concentrations. As can be seen in Figure 10, as the proportion of natural gas increases, so does the fraction of nitrogen oxides. Figure 11's distributions in a bowl meridional section further demonstrate that, due to a rapid growth to a complete combustion immediately after the pilot injection start, methane combustion in the 90% case causes greater temperature peaks in vicinity to TDC than in the 50% case. As can be seen in Figure 12, the 90% scenario has the largest concentration of NO at the same crank angle. Figure 13 displays the trends in CO and CO₂ levels. The 90% scenario has the best CO value, while the Full Diesel case has the highest CO value. The changes in CO₂ concentrations are consistent with the computed indices shown in Table 7.

Table 6. Simulations at 2000 rpm with varying CH₄ concentrations

CH ₄ %	ϕ	m_{gr} (mg/cyc)	$m_{tot fuel}$ (mg/cyc)	Pilot Inj. Start ATDC	Main Inj. Start ATDC	α
0	0.468	21.80	21.8	-18.5	2.5	31.88
28	0.505	15.58	21.64	-18.0	2.5	30.77
50	0.530	10.88	21.76	-18.0	3.0	30.19
72	0.531	5.60	20.00	-18.0	2.5	31.10
90	0.531	2.02	20.20	-18.0	2.6	30.10

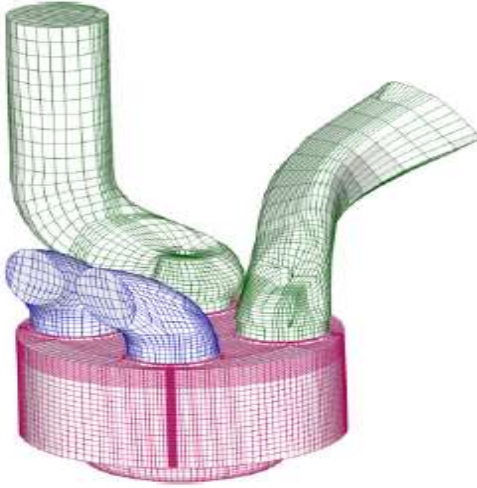


Figure 6. Computational domain and structured mesh

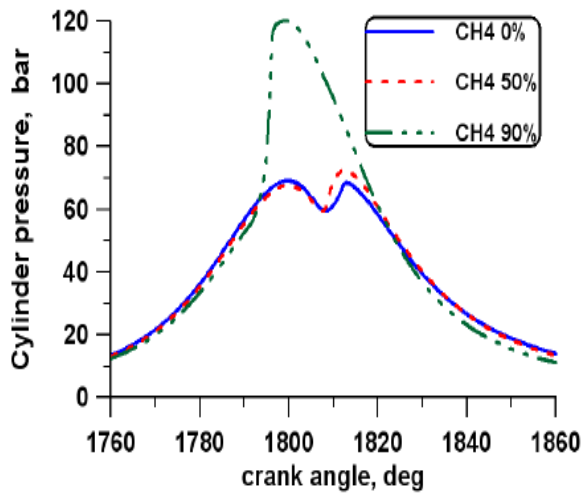


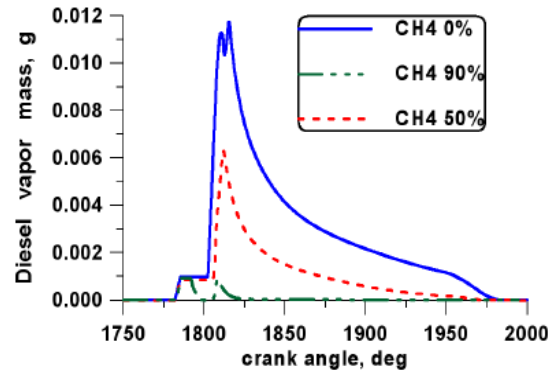
Figure 7. In-cylinder pressure cycles in FD and DF mode at different NG rates

Table 7. Numerical results

CH ₄ %	IMEP (bar)	T _{ent} [K] at EVO	CO ₂ % at EVO	CO ₂ Index [kg/kWh]
0	6.77	1093	10.14	0.750
28	6.49	1022	9.95	0.765
50	6.77	1036	9.27	0.686
72	6.61	1275	8.28	0.625
90	6.03	1243	7.95	0.658

4. A numerical - experimental comparison

Finally, we've compared our numerical results to those from experiments, and we see that they agree quite well in terms of in-cylinder pressures, which show amplified peaks at the highest values of methane (or NG) contents (Figure 14). In particular, there is a correlation between experimental and numerical pressures. For low methane ratios (i.e., up to 50%), the pressure cycle has a double peak because the main injection of diesel oil is delayed. This is the general trend for all given NG rates. Similar patterns indicate that the primary diesel injection is responsible for sparking the methane-air combination to life. Furthermore, both the calculated and experimental curves are representative of a lean progression of combustion that is similar to the HCCI idea. Contrarily, as predicted, for NG 90%, mixture ignition occurs after the pilot injection and so is early relative to the TDC. This clarifies the single peak and, more importantly, the more rapid increase in pressure that is consistent with the numerical simulation. However, the latter is able to predict a much more severe behavior that is close to a knocking inception, despite only showing a qualitative accordance with the experimental curve (likely due to a different wall temperature regime). These findings also suggest that, regardless of the engine's design, CFD-based activities may accurately forecast the engine's reaction to varying rates of natural gas in dual fuel operation.



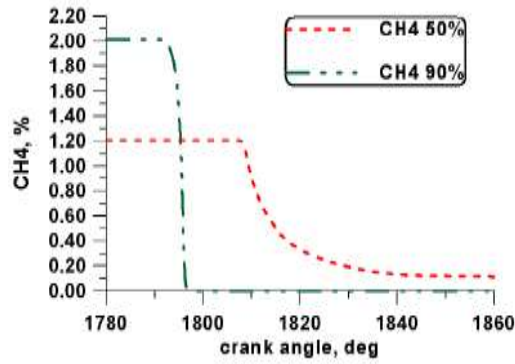


Figure 8. Diesel Vapor mass and CH4 consumption rate

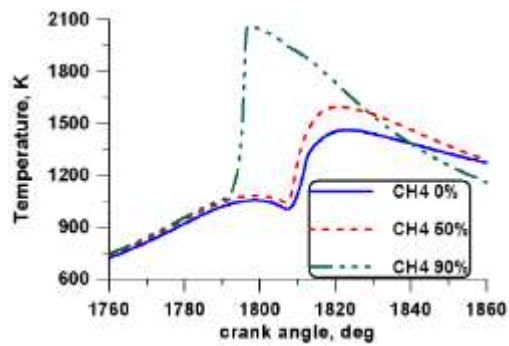


Figure 9. Average temperatures at different CH4 contents

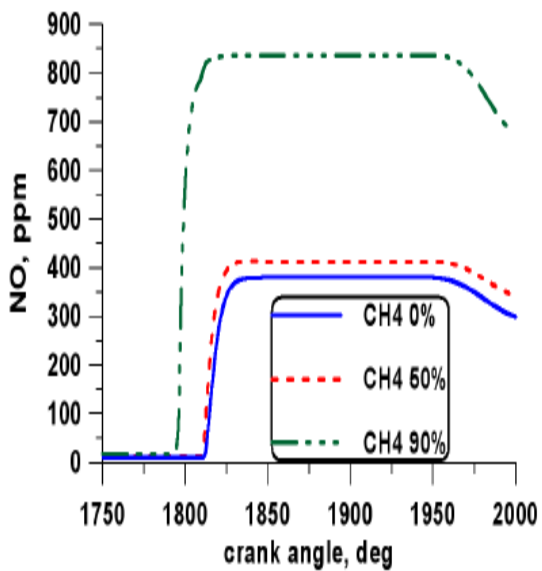


Figure 10. Computed NO fractions at different CH4 contents

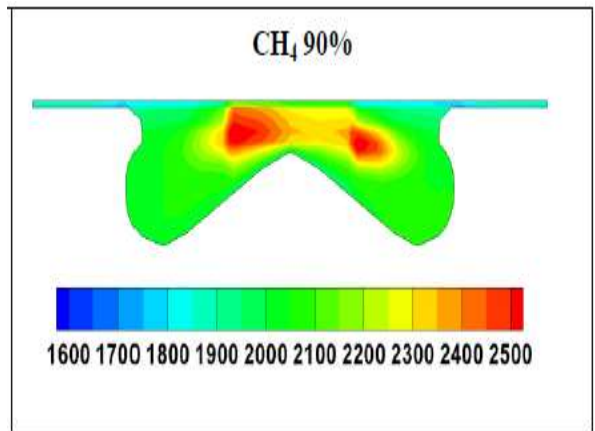
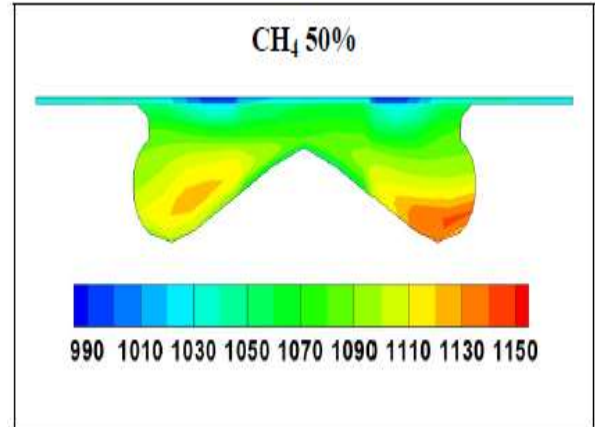
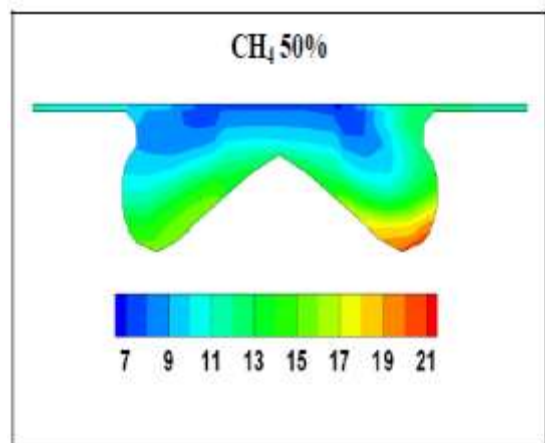


Figure 11. Temperature distributions [K] for different CH4 ratios at TDC



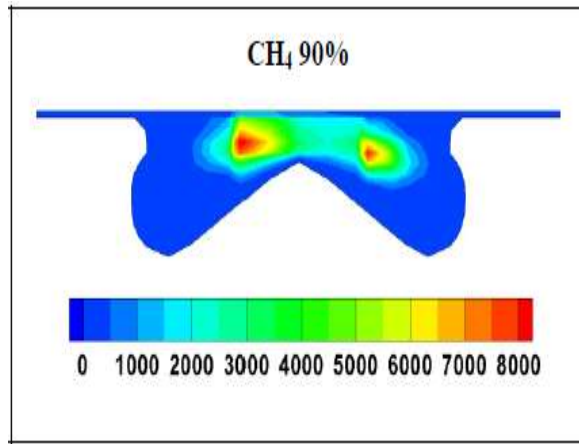


Figure 12. NO distributions [ppm] for different CH₄ ratios at TDC

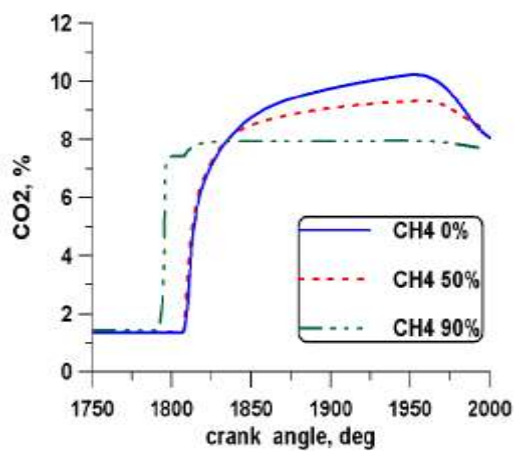
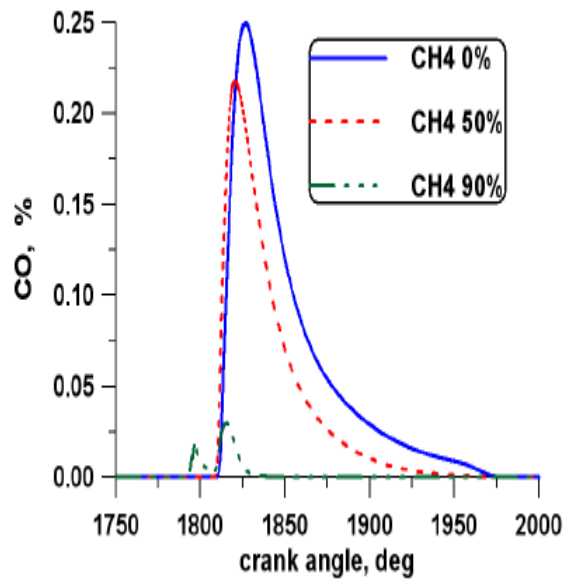


Figure 13. Computed CO and CO₂ fractions at different NG contents

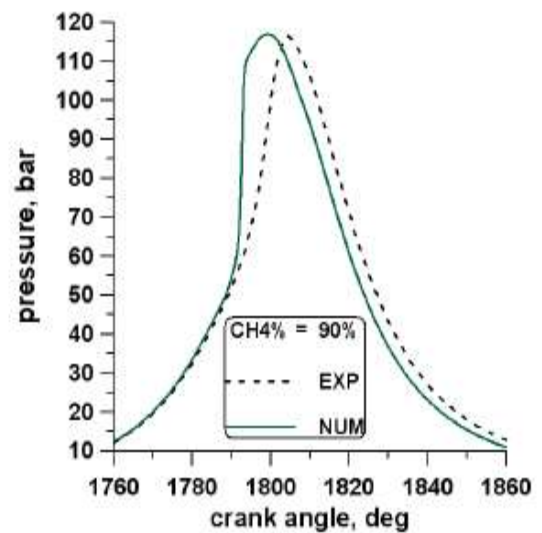
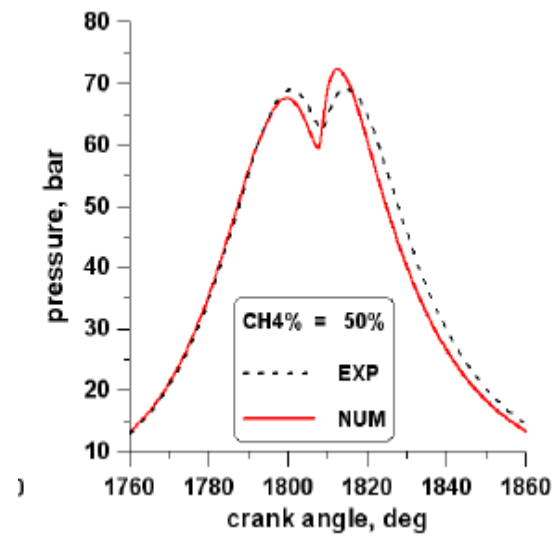
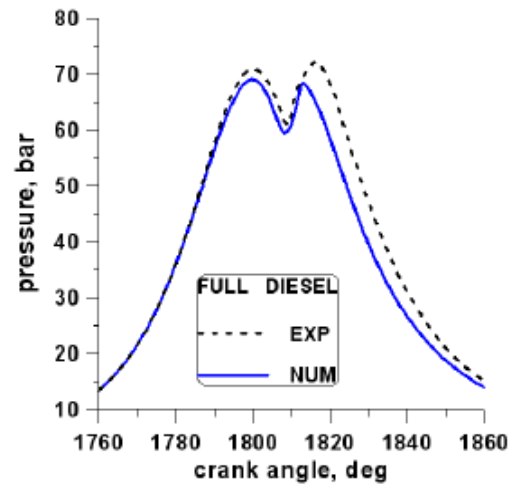


Figure 14. Comparison of Pressure cycles at different CH₄ rates

5. Conclusions

Comprehensive investigation of diesel engine reaction to dual fuel mode with changing rates of natural gas in the fuel air mixture entering the cylinders was performed by the authors using a combination of experimental data and numerical findings from CFD instances. Evidence from both methods shows that, given NG rates, when the fuel-to-air ratio is between 50 and 60 percent, the engine behaves virtually identically to when it is running at maximum diesel power in terms of lean combustion development and nitric oxide generation. However, when the NG rate is increased to 70–90%, the engine exhibits behavior similar to that of spark ignition engines near knocking conditions, characterized by an abrupt consumption of the natural gas in the reacting mixture and, consequently, a steep pressure rise. The investigations also revealed that the complete spectrum of dual fuel mode shows a significant rise in CO output. There is a decrease in the CO₂ indices in both the computational and experimental data. The authors conclude that the reasonable agreement shown between numerical and experimental data is the most important indicator arising from this effort. Actually, both types of results have demonstrated the engine's noticeably different behavior when the natural gas ratio is increased. Therefore, the authors will be turning to experiments in the future to verify the suggestions from the CFD based analysis, but for now, they will continue to rely on the numerical studies as an efficient tool for searching optimal solutions for the dual fuel operation (i.e. the most feasible NG rate, the optimal injection timing of the diesel oil, etc.). Several other liquid and gaseous fuels will be added to the methodology as well, including LNG, biodiesel, and biogases.

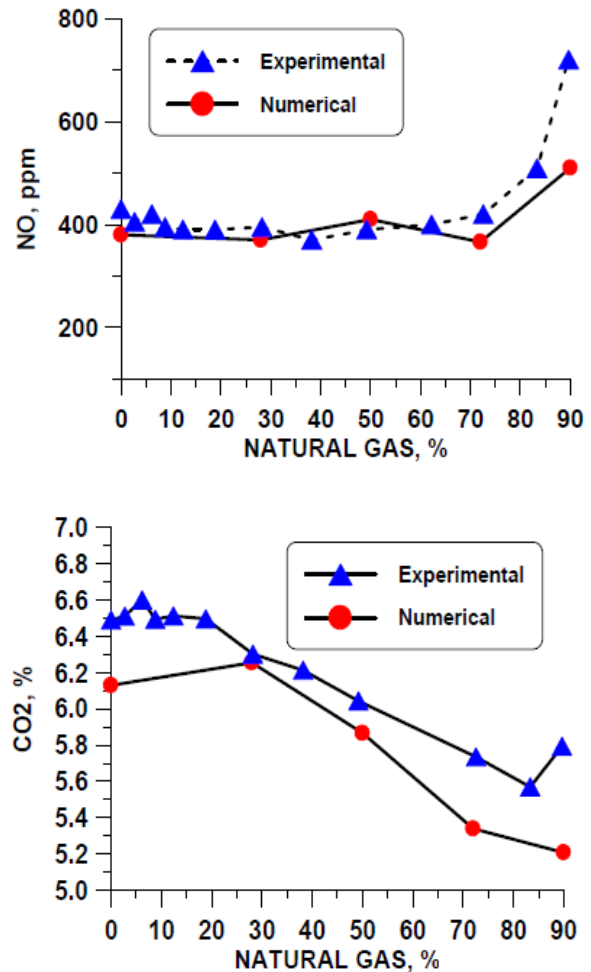


Figure 15. Comparison of experimental and numerical NO and CO₂ fractions

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