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Effect of Oxygen Enriched Air Combined with EGR on Performance Parameters and Diesel Engine Emissions

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Abstract
In this study, the combined effect of oxygen enrichment and exhaust gas recirculation (EGR) on combustion performance and pollutant formation in a direct-injection diesel engine was investigated. The main objective was to analyze the simultaneous influence of increased oxygen concentration and EGR application on improving the combustion process and reducing exhaust emissions. Numerical simulations were conducted using AVL-FIRE software on an AVL 5402 single-cylinder, four-stroke, and direct-injection diesel engine. The Shell ignition model and the Zeldovich NOx model were employed to predict temperature, pressure, soot, and NOx emissions, and the results were validated against experimental in-cylinder pressure data. The results show that the desired NO output is achieved at 1400 rpm using 21.5 to 22.5% oxygen enrichment and 5 to 10 percent EGR, and at 1800 rpm using 21 to 22% oxygen enrichment and 10 to 15% EGR. Also, in the case of using cold exhaust EGR, the desired NO can be achieved under 1400 rpm conditions using 21.5 to 22.5% oxygen enrichment and 10 to 15% EGR, and at 1800 rpm engine speed using 21 to 22% oxygen enrichment and 15 to 20% EGR.

Keywords: Diesel Engine, Oxygen Enrichment, Exhaust Gas Recirculation, Pollutant Emissions.

1. Introduction

The continuous development of diesel engines is primarily driven by the dual necessity of enhancing fuel efficiency and power output while simultaneously complying with increasingly stringent emission regulations. Among various strategies, intake oxygen enrichment has been studied for decades as an effective method to influence combustion chemistry and particulate formation. Early experimental work demonstrated that enriching the intake with oxygen accelerates oxidation and reduces soot emissions, although it inevitably increases in-cylinder temperatures and thereby promotes NOx formation [1]. This dual effect underscores the importance of carefully balancing oxygen enrichment levels to maximize combustion efficiency without surpassing emission limits.

Subsequent investigations confirmed these trade-offs through both experimental and computational approaches. Donahue and Foster [2] highlighted that moderate enrichment (approximately 21–22% O2) in direct injection diesel engines significantly decreases particulate emissions, whereas higher oxygen fractions cause disproportionate increases in NOx. Later simulation studies using advanced CFD platforms such as AVL-FIRE provided quantitative insights, demonstrating that oxygen concentrations near 24% yield favorable combustion while further enrichment results in diminishing soot reduction and excessive NOx formation [3]. More recently, controlled-atmosphere flame analyses reinforced that oxygen concentration strongly modifies flame structure and soot precursor dynamics, necessitating complementary NOx control measures [4].

Exhaust gas recirculation (EGR) remains the most established method for mitigating NOx emissions in diesel engines. Its influence on combustion kinetics and soot reactivity is well documented, with increased EGR generally lowering peak combustion temperatures and suppressing NOx, albeit at the expense of higher soot formation. Strategies combining oxygen enrichment with EGR have been proposed to simultaneously exploit enhanced soot oxidation and reduced thermal NOx pathways. Kapusuz et al. [5], for example, showed that coupling oxygen enrichment with inlet humidification or cooling can provide a more favorable balance between soot and NOx emissions, though systematic analyses of hot versus cold EGR under varying enrichment levels remain limited.

The present study addresses this gap by conducting a comprehensive numerical investigation of diesel combustion under simultaneous oxygen enrichment and both hot and cold EGR conditions across two engine speeds. The simulations employ AVL-FIRE with established combustion and pollutant formation sub-models and are validated against in-cylinder pressure data. The central objective is to identify practical operating regimes that sustain the benefits of oxygen enrichment—improved combustion and soot reduction—while mitigating the concurrent rise in NOx emissions. In this way, the work extends and integrates the findings of earlier experimental and computational studies into a systematic framework for dual intake modification strategies.

2. Governing Equations

The general forms of the continuity, momentum, energy, and species conservation equations are respectively expressed as follows (Equations 1 to 4).

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \nabla.(\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla P + \nabla.\tau \tag{2}$$

$$\rho \frac{\partial E}{\partial t} + \nabla.(\rho E \boldsymbol{u}) = -\nabla(p\boldsymbol{u}) + \nabla.(D_T \nabla T) + \rho \sum_{k=1}^{N} I_k h_{\boldsymbol{k}} + \nabla.(\boldsymbol{u}.\tau) + \dot{E}_{ex} \tag{3}$$

$$\rho \frac{\partial Y_k}{\partial t} + \nabla.(\rho \boldsymbol{u} Y_k) = -\nabla.I_k + \dot{\omega}_k \tag{4}$$

Where t is the time, u the velocity vector, ρ the density, τ the stress tensor, E the internal energy of the mixture, T the temperature, P the pressure, I_k the turbulent diffusive flux of species k, h_k the specific enthalpy of species k, $\dot{E}_{ex}$ the energy input to the system, Y_k the mass fraction of species k, and $\dot{\omega}_k$ the production rate of species k. The turbulence equations are implemented using the k–ε model, where k denotes the turbulent kinetic energy and ε the turbulence dissipation rate (Equations 5 and 6).

$$\frac{\partial}{\partial t}(\rho k) + \nabla.(\rho k \mathbf{u}) = \nabla.\left(\mu + \frac{\mu_t}{\sigma_k}\nabla k\right) + \tau^t : \nabla \boldsymbol{u} - \rho\varepsilon \tag{5}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla.(\rho \varepsilon \mathbf{u}) = \nabla.\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\nabla \varepsilon\right) + \frac{\varepsilon}{k}\left(C_{1\varepsilon}\tau^t : \nabla \boldsymbol{u} - C_{2\varepsilon}\rho\varepsilon\right) \tag{6}$$

3. Simulation

Extended In the simulation section, the problem was modeled using the ESE-DIESEL module of AVL-FIRE software for a single cylinder of the AVL 5402 engine (single-cylinder, four-stroke, turbocharged, direct injection). To reduce computational time, the simulation was performed only from the intake valve closing (IVC) to the exhaust valve opening (EVO), and the geometry was considered axisymmetric and simplified. Only one combustion chamber was modeled, and the fuel injection rate along with the mass flow parameters of the inlet stream were kept constant in all cases to maintain a constant equivalence ratio. Variations in oxygen fraction were limited to increasing the oxygen concentration in the intake air while maintaining the total pressure. The mesh and boundary conditions of the combustion chamber are shown in Figure 1, and the initial wall temperatures are listed in Table 1.

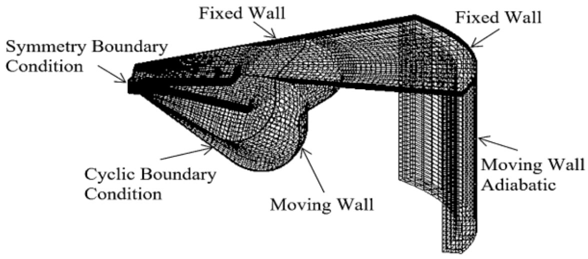

Figure 1. Mesh and boundary conditions of the combustion chamber.

Table 1. Wall boundary conditions

Boundary Conditions		FIRE	Boundary
Descrip	Type		
Moving Mesh	Wall	BND_Piston	Piston
Zero Velocit	Wall	BND_Liner	Cylinder Liner
-	Symmetric	BND_Axis	Axis
Periodic	Inlet/Outlet	BND_Segment	Segment
Moving Mesh	Wall	BND_Comp_Vol	Housing
Zero Velocit	Wall	BND_Head	Cylinder Head

4. Results and Discussion

The numerical simulations were first subjected to mesh-independence testing, where negligible differences were observed between the 52,000- and 67,000-cell grids, and the 52,000-cell mesh was therefore selected to balance accuracy and computational cost. Validation against experimental in-cylinder pressure and exhaust species concentrations confirmed the reliability of the model. The effect of oxygen enrichment on the combustion process is illustrated in Figure 2, where the increase in inlet oxygen fraction significantly elevates the peak in-cylinder temperature and shifts it to earlier crank angles, indicating reduced ignition delay and prolonged high-temperature residence time. The corresponding pressure traces (Figure 3) show a similar trend, with higher peak pressure values and an earlier pressure rise, reflecting accelerated heat release and higher power potential at the expense of increased mechanical loading.

Further insight into the spatial distribution of

combustion characteristics is provided in Figure 4, which demonstrates that oxygen enrichment enhances both the extent and intensity of high-temperature zones inside the cylinder. These regions correlate directly with higher nitric oxide (NO) formation, confirming the strong thermal pathway governing NO production. Quantitative comparisons in Table 2 show that oxygen enrichment yields considerable soot reduction, reaching up to 60% compared with the baseline, but this improvement is accompanied by a sharp rise in NO emissions, exceeding 800% at an oxygen concentration of 27%. The trade-off between soot oxidation and NO promotion is thus a central feature of oxygen-enriched combustion.
To mitigate this drawback, exhaust gas recirculation (EGR) was introduced in combination with oxygen enrichment. The results demonstrate that EGR reduces peak temperature and pressure through dilution and increased heat capacity, thereby suppressing NO formation by more than 38% at 20% EGR. However, this suppression also diminishes the soot oxidation benefit provided by oxygen enrichment. Cold EGR was found to be more effective than hot EGR in reducing both soot and NO while maintaining higher charge density and combustion efficiency.

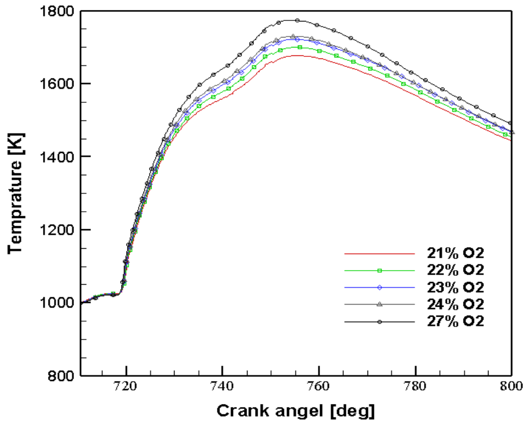

Figure 2. Temperature variations versus crank angle at different enrichment percentages

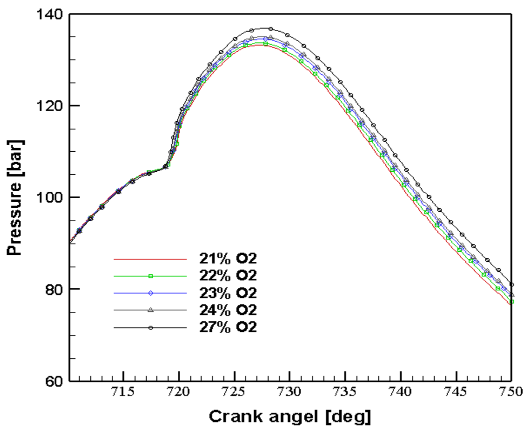

Figure 3. Pressure variations versus crank angle at different enrichment percentages

Overall, the results highlight that neither oxygen enrichment nor EGR alone can simultaneously optimize soot and NO emissions. Instead, a combined strategy provides a viable balance. Specifically, moderate oxygen enrichment (approximately 25%) combined with modest levels of EGR (~10%) emerged as the most favorable compromise, achieving significant soot reduction without incurring the excessive NO penalty associated with oxygen enrichment alone.

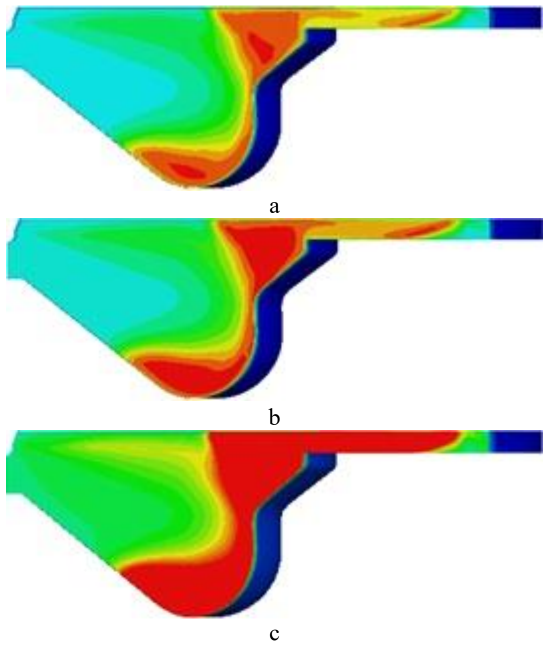

Figure 4. Temperature contours inside the combustion chamber at 16° CA ATDC and oxygen percentages: (a) 21%, (b) 24%, (c) 27%

Table 2. Maximum variations in temperature, pressure, soot emission, and NO emission as a function of the increase in oxygen enrichment percentage.

Change in Maximum Value (%) (Increase ↑ / Decrease ↓)				Enrichment (%)	Row
NO ↑	**Soot ↓**	**Pressure ↑**	**Temperature ↑**		
46.4	3.3	0.4	0.9	21	1
132.1	8.0	0.8	2.2	22	2
225.0	21.1	1.5	3.5	23	3
333.9	26.3	1.9	4.0	24	4
805.4	60.1	3.1	6.6	27	5

5. Conclusions

The present study aims to investigate the simultaneous effects of intake air enrichment with oxygen and exhaust gas recirculation (EGR) on the performance of a turbocharged direct-injection diesel engine using AVL-FIRE software. The combination of these two important technologies under various operating conditions, along with a comparative analysis of hot and cold EGR and their effects on engine power, fuel consumption, and emissions, constitutes one of the main novelties of this research. Key findings under different engine conditions, which can aid in the design of effective emission control systems and the selection of optimal strategies in the automotive and diesel industries, are summarized as follows:

- Comparison of the present simulation results with experimental data from other studies showed good agreement, indicating that the current simulation outcomes can be reliably used in future research.
- Increasing the oxygen concentration from 21% to 27% resulted in a rise in peak in-cylinder pressure from 2.85 to 8.94 bar (an increase of 2.11%), due to faster combustion and higher released energy.
- The same increase in oxygen concentration raised the peak temperature from 2250 K to approximately 2385 K.
- In the absence of EGR, soot formation decreased from 0.45 to 0.16 (a reduction of 64.4%) with increasing oxygen, attributed to enhanced oxidation of heavy hydrocarbons.
- Conversely, NO concentration increased with higher oxygen levels, exceeding 1680 ppm at 27% oxygen, due to higher temperatures and longer residence times in hot regions.
- The use of EGR up to 20% led to more than a 38% reduction in NO formation without significant negative effects on in-cylinder pressure or temperature.
- The optimal combination of 25% oxygen and 10% EGR provided the best balance between soot reduction and NO control, resulting in approximately 1140 ppm NO and 0.19 soot.

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