Development of High Efficiency and Low Emission Low Temperature Combustion Diesel Engine with Direct EGR Injection

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Abstract. Focus on energy and environmental sustainability policy has put automotive research & development directed to developing high efficiency and low pollutant power train. Diffused flame controlled diesel combustion has reach its limitation and has driven R&D to explore other modes of combustions. Known effective mode of combustion to reduce emission are Low temperature combustion (LTC) and homogeneous charge combustion ignition by suppressing Nitrogen Oxide(NOₓ) and Particulate Matter (PM) formation. The key control to meet this requirement are chemical composition and distribution of fuel and gas during a combustion process. Most research to accomplish this goal is done by manipulating injected mass flow rate and varying indirect EGR through intake manifold. This research paper shows viable alternative direct combustion control via co-axial direct EGR injection with fuel injection process. A simulation study with OpenFOAM is conducted by varying EGR injection velocity and direct EGR injector diameter performed with under two conditions with non-combustion and combustion. n-heptane (C₇H₁₆) is used as surrogate fuel together with 57 species 290 semi-detailed chemical kinetic model developed by Chalmers University is used for combustion simulation. Simulation result indicates viability of co-axial EGR injection as a method for low temperature combustion control.

1. Introduction
The main contributors to green house gases are power generation and transportation industries. Diesel engine is considered as one of the most efficient power plant widely used in transportation industries contributed by its high compression ratio and low throttling loses design [1]. Study showed an estimate of 6% to 32% of Nitric Oxide (NOₓ) emission is contributed by passenger automobile in overall and NOₓ and Particulate Matter(PM) is by-product a conventional diesel combustion engine [2]. Extensive research has been done to reduce NOₓ and PM by reducing flame temperature. It has been a challenging task to increase engine thermal efficiencies while suppressing combustion temperature as both NOₓ and PM formation has strong relation to combustion temperature [3]. Research this direction are also known as Low Temperature Combustion(LTC), High Temperature Air Combustion (HTAC), Flameless Oxidation (FLOX), Low Nitrix Oxide Injection (LNI), Homogeneous Charged Compressed Ignition(HCCI), and Mild Combustion.
2. Background Studies
Although diesel engine are an efficient powertrain, but it also produces high NOx and PM emission. Improvement to conventional diffused flame control diesel engine combustion has reached its limitation as described in figure 1. Compressed stroke of a conventional diesel engine compresses rises combustion air above diesel fuel autoignition temperature. Fuel injection takes place slightly before Top Dead Center (TDC) when the injected fuel mixed with hot compressed combustion air forming air-fuel mixture. Autoignition takes place at stoichiometric air-fuel mixture forming high temperature region known as flame front. Remaining combustion is maintained by premixed turbulent jet surrounded diffused flame [2]. This high flame front temperature forms NOx and rich fuel ratio entrained behind the flame front forms PM in such combustion process. NOx formation are mainly contributed from thermal with presence of oxygen and hydroxyl radical [4, 5]. PM formation follow different path where it begins with fuel pyrolysis with unburned fuel is exposed to high temperature at low oxygen condition [2].

Figure 1. Conventional direct injection diesel spray combustion schematics. [1]

Figure 2. Pollutant formation condition and distribution. [6]

A systematic simulated research approach indicates that highest efficiency were attained from increase of compression ratio, decrease of equivalence ratio and increase of EGR [7]. HCCI and LTC combustion mode are able to meet similar performance characteristics [6]. HCCI suppresses combustion temperature by low equivalence ratio. However, HCCI requires complex premixed fuel-air preparation for mixture homogeneity prior to combustion which limits such application to low load condition and a challenge for high load condition [1]. LTC involves high EGR to keep oxygen concentration low enough to suppress flame front development but high equivalence ratio increases fuel pyrolysis. Hence, rapid mixing of fresh combustion air with fuel vapor cloud decreases equivalence ratio with direct EGR injection at the right injection velocity and timing to prevent soot and NOx formation as shown in line (b) in figure 2. Objective of this investigation is to identify the prospect of direct EGR injection in developing low emission high efficiency diesel spray combustion.

3. Research Methodology
The simulation platform applied for this research is Open-Sourced Field Operation and Manipulation (OpenFOAM) computational fluid dynamics simulation software with a modified dieselFoam solver to model diesel spray breakup, fuel evaporation and gas dynamics. The simulated model implemented for gas dynamic and thermodynamics for diesel spray combustion model is based on approach used in this research in diesel spray combustion [13]. The primary reference fuel used as surrogates fuel is n-heptane together with CO2 as EGR is modelled with reduced chemical kinetic model developed by Golovitchev (57 species, 290 reaction) [12] for this parametric research to identify optimal
configuration. The boundary conditions are as listed in table 1. Case 1-9 are setup by varying co-axial nozzle diameter and EGR injection velocity and compared with conventional diesel spray combustion, Case 10 & 11. Co-axial injection is intended to improve fuel evaporation and mixing promoting LTC to reduce both NOx and soot formation at the same time. The results is compared with turbulent flame controlled diesel spray combustion.

| Boundary Conditions | Direct EGR Injection Condition |
|---------------------|--------------------------------|
| Air Concentration   | 21% O2, 79% N2                |
| Air Temperature     | 1000K                          |
| Injection Configurations | | |
| Pressure            | 150MPa                         |
| Duration            | 6.8 ms                         |
| Reference Fuel      | n-Heptane(nC7H16)              |
| Nozzle Diameter     | 0.1mm                          |
| EGR Temperature     | 950K                           |
| EGR Duration        | 5.5ms                          |
| Case                | EGR Nozzle Diameter (mm)       |
| 1                   | 0.2                            |
| 2                   | 0.2                            |
| 3                   | 0.2                            |
| 4                   | 0.3                            |
| 5                   | 0.3                            |
| 6                   | 0.4                            |
| 7                   | 0.4                            |
| 8                   | 0.6                            |
| 9                   | 0.6                            |
| 10 & 11             | Reference with Golovitchev Reduced Mechanism |
| 11                  | Reference with full n-Heptane Chemkin Model |

4. Result and Discussion

![Figure 3. Peak combustion temperature.](image)

![Figure 4. Formed NO comparison.](image)

![Figure 5. Max T & NO vs time - Case 10.](image)

![Figure 6. Mean HRR & NO vs time - Case 10.](image)
Figure 3-4 are summary for all cases. Comparison between Golovitchev reduced mechanism (Case 10) and full chemkin model (Case 11) in figure 3, shows agreement in modelling n-heptane diesel spray combustion chemistry. All co-axial EGR injection case showed reduced peak combustion temperature and negligible NO formation shown in figure 3 & 4. Co-axial injection suppressed thermal NO formation by reducing N₂ residence time exposed to high combustion temperature and suppresses high combustion temperature flame front by rapid mixing induced by co-axial direct EGR injection. Case 10 in figure 5 indicates conventional combustion maintained elevated peak combustion temperature above thermal NO formation limit produces continuous increase of NO formation after ignition if compared to Case 1 from figure 7 that showed lower peak combustion temperature with negligible NO formation. Case 10 from figure 6 shows high HRR after ignition indicating pre-mixed flame combustion later followed by lower mean HRR turbulent diffused flame mixing controlled combustion. Case 1 from figure 8 showed reduced ignition delay with co-axial injection with prolonged premixed combustion duration with lower premixed combustion mean HRR and followed lower combustion temperature mixing controlled combustion. This could be explained as co-axial injection break up fuel droplets and promotes fuel evaporation reducing ignition delay. High injection velocity sustains longer premixed combustion duration and a reduces the surface volume of mixture at stoichiometric at an instance unlike conventional diesel spray combustion.

Case 1-3 compares different injection velocities between 100m/s(Case 1), 150m/s(Case 2) and 200m/s (Case -3) indicates higher co-axial injection velocity above Case 1 showed reduced or negligible premixed combustion and maintains combustion at low temperature mixing controlled combustion. Case 1, Case 4, Case 6, Case 8 compares different EGR injection volume with larger EGR injection nozzle. Results showed higher EGR injection volume showed reduced or negligible premixed combustion. In both situation of reduced or negligible premixed combustion are unfavourable as it would diminish the benefits of HCCI combustion at start of injection and solely relies on LTC to maintain combustion. Preliminary conclusion indicates low EGR injection volume at lower velocities describe in Case 1 is optimal at this point. Further investigations with lower EGR volume, EGR injection velocities, EGR injection duration are necessary

5. Conclusion

There has been great interest in LTC and HCCI combustion for high efficiency and low pollution emission diesel engine application, however, posed as great challenge to combustion control. Simulated data indicates that direct EGR Injection has the ability to directly control mixing controlled combustion instead of high emission conventional high diffused flame combustion. Direct EGR injection could serve as a mean of combustion control to expand the range of engine operation under low temperature flameless combustion mode with high efficiency and low emission.
References

[1] J. E. Dec, "Advanced compression-ignition engines - Understanding the in-cylinder processes," *Proceedings of the Combustion Institute*, no. 32, pp. 2727-2742, 2009.

[2] D. R. Tree and K. I. Svensson, "Soot processes in compression ignition engines," *Progress in Energy and Combustion Science*, no. 33, pp. 272-309, 2007.

[3] S. Gan, H. K. Ng and K. M. Pang, "Homogeneous Charge Compression Ignition (HCCI) combustion: Implementation and effects on pollutants in direct injection diesel engines," *Applied Energy*, no. 88, pp. 559-567, 2011.

[4] S. Saravanan, G. Nagarajan, S. Anand and S. Sampath, "Correlation of thermal NOx formation in compression ignition (CI) engine fuelled with diesel and biodiesel," *Energy*, no. 42, pp. 401-410, 2012.

[5] S. C. Hill and L. D. Smoot, "Modeling of nitrogen oxides formation and destruction in combustion system," *Progress in Energy and Combustion Science*, no. 26, pp. 417-418, 2000.

[6] R. Ho, M. Yusoff and K. Palanisamy, "Trend and future of diesel engine: Development of high efficiency and low emission low temperature combustion diesel engine," in *4th International Conference on Energy and Environment 2013 (ICEE 2013)*, 2013.

[7] J. A. Caton, "The thermodynamic characteristics of high efficiency, internal combustion engines," *Energy Conversion and Management*, no. 58, pp. 84-93, 2012.

[8] J. Wunning and J. Wunning, "Flameless Oxidation to Reduce Thermal NO-Formation," *Prog. Energy & Combustion*, vol. 23, pp. 81-94, 1997.

[9] R. Weber, J. P. Smart and W. v. Kamp, "On the (MILD) Combustion of Gaseous, Liquid, and Solid Fuels in High Temperature Preheated Air," in *Proceedings of the Combustion Institute*, 2005.

[10] C. Tang, Z. Tang, P. Ma, Q. Lin and X. Xing, "Research on the Three Different Kinds of Technologies to Achieve Flameless Combustion and Their Applications," *IEEE*, pp. 978-1-4244-2487-0/09, 2009.

[11] L. M. Pickett, "Low flame temperature limits for mixing-controlled Diesel combustion," *Proceedings of the Combustion Institute*, no. 30, pp. 2727-2735, 2005.

[12] V. Golovichev, "Mechanisms (combustion chemistry);," [Online]. Available: http://www.tfd.chalmers.se/~valeri/MECH.html. [Accessed 15 March 2014].

[13] R. Novella, A. Garcia, J. Pastor and V. Domenech, "The Role of Detailed Chemical Kinetics on CFD Diesel Spray Ignition and Combustion Modelling," *Mathematical and Computer Modelling*, vol. 54, pp. 1706-1719, 2011.

[14] J. Wunning, "Flameless Oxidation," in *6th HiTACG Symposium*, Essen - Germany, 2005.