Trend and future of diesel engine: Development of high efficiency and low emission low temperature combustion diesel engine.

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Abstract. Stringent emission policy has put automotive research & development on developing high efficiency and low pollutant power train. Conventional direct injection diesel engine with diffused flame has reached its limitation and has driven R&D to explore other field of combustion. Low temperature combustion (LTC) and homogeneous charge combustion ignition has been proven to be effective methods in decreasing combustion pollutant emission. Nitrogen Oxide (NOₓ) and Particulate Matter (PM) formation from combustion can be greatly suppressed. A review on each of method is covered to identify the condition and processes that result in these reductions. The critical parameters that allow such combustion to take place will be highlighted and serves as emphasis to the direction of developing future diesel engine system. This paper is written to explore potential of present numerical and experimental methods in optimizing diesel engine design through adoption of the new combustion technology.

1. Introduction

One of the main sources of pollutant emission are contributed by diesel combustion from either power generation or transports. Compressed ignition engine such diesel engine is one of the most efficient power plant for transportation due to its relatively high compression ratios and lack of throttling losses [1]. As result, wide applications of such diesel engine for transportation are one of the most noTable sources of pollution emission. It is reported that excess of 30% of total passenger automobile in European countries are powered by diesel engine [2]. Research on effects of diesel combustion indicates emissions of nitrogen oxide emission (NOₓ) and particulate matter (PM) that has adverse effect on human health [3]. Overall, it is estimated that 6%-32% of NOₓ is contributed by passenger automobile. Exhaust NOₓ emission is about 300 times stronger greenhouse effect if compared to carbon dioxide(CO₂) [3]. For the past decades, extensive research has been done for NOₓ and PM reduction. Increasing engine thermal efficiencies while suppressing pollutant emission are very challenging as it has contradicting objectives. Thermal efficiency, NOₓ and PM are strong functions of temperature and equivalence ratio. Engine efficiency and NOₓ emission increases with combustion temperature while reduction of flame temperature reduces soot oxidation increasing soot emission [4].

To suppress NOₓ, a relatively new combustion technology known as low temperature combustion (LTC) has been introduced. Application for burners and furnaces has been shown to have the potential of reducing NOₓ and soot formation [6]. This mode of combustion has been researched and developed
under different names in different countries such as High temperature air combustion (HTAC) in Japan, Flameless Oxidation (FLOX) in Germany, Low Nitric Oxide Injection (LNI) in United State of America and Mild Combustion in Italy [7]. This mode of combustion in diesel engine is further researched under HCCI combustion system [8]. However, there are limited successes due to complex fluid and chemical interaction under engine dynamic state condition.

2. Background Studies
Compressed ignitions are the most fuel-efficient engines ever developed for transportation industries mainly attributed by its relatively high compression ratios and reduced throttling losses. However, diesel engine comes with drawback of high NO\textsubscript{x} and PM has made it a challenge to the industry to comply to stringent emission legislation. Numerous studies have been done on this area where efficiencies have increased and pollutant emissions have decreased substantially [1]. However, improvement to conventional diesel engine has come to a limitation as describe in Figure1. A reduction of pollutant emission is limited with conventional diesel combustion. Piston compression stroke rises combustion air above diesel fuel autoignition temperature. Fuel injection takes place during combustion stroke with fuel ignited when fuel vaporization achieves ignition equivalence ratio producing lifted, partially premixed turbulent jet surrounded by a diffusion flame [4]. Stoichiometric mixture is oxidized and combusted with high temperature diffused flame resulting in NO\textsubscript{x} formation and reduces the available oxygen for remaining fuel entrained in the flame resulting in soot formation. To meet increasing demand of stricter emission and efficiencies, researches are directed towards low temperature combustion.

![Figure 1](image1.png)  
**Figure 1.** Conventional direct injection diesel spray combustion schematics[1].

![Figure 2](image2.png)  
**Figure 2.** NO\textsubscript{x} and PM formation region corresponding to equivalence ratio at temperature[1].

A systematic approach from numerical simulation indicates that highest efficiency were attained from increase of compression ratio, decrease of equivalence ratio and increase of EGR[9].

2.1. Homogeneous Charge Compressing Ignition (HCCI)
HCCI is based on pollutant emission reduction concept by suppressing peak flame temperature by having self-ignition of premixed homogeneous charge in combustion chamber for homogeneous combustion. Maximum temperature of the charge is kept low by means of low equivalence ratio with or without exhaust gas recirculation (EGR) dilution [8]. This mode of combustion offers significant amount of pollutant emission reduction. HCCI are also classified under LTC but distinction is HCCI suppresses combustion temperature with lean combustion with low equivalence ratio. Applications of HCCI on diesel engine are limited to the ability of diesel engine in-cylinder flow process to replicate mixture homogeneity throughout the combustion volume prior to multiple point autoignition. Before
HCCI combustion can be fully applied to automotive diesel engine, main challenge has to be solved. They are poor low-loads combustion efficiency, limited operation range, poor understanding of limiting factors and poor combustion control under transient condition [1]. This limitation is primarily due to complex chemical kinetic controlled combustion coupled with complex in-cylinder fluid interaction and condition that determines the autoignition timing and combustion processes [10]. Optical imaging on HCCI system indicates that soot formation is dependent on oxygen concentration of fuel and OH* radical is responsible for NO\(_x\) formation [11].

An experimental and numerical investigation was conducted on correlation on the effect reactant temperature and mixture stratification to HCCI combustion characteristics [10]. The research indicates HCCI combustion consisted of two stages. First stage of low temperature heat release combustion and later followed by high temperature heat release combustion. Different port injection strategies infer that autoignition advances with mixture in-homogeneity. This result in large temperature stratification causes by low mixing duration from short ignition delay. Chemiluminescence intensity increases with shorter ignition delay indicating OH* formation concentrated at different localised stratified region. Turbulence generated from higher engine speed produced higher homogeneous temperature distribution. Mixture autoignition is also dependant on thermal stratification. Lower wall temperature causes large thermal stratification at wall region. Strong heat transfer to lower wall temperature to have lower reaction rate. Comparison with different wall temperature indicates that chemical kinetic reaction has been "frozen" due to low temperature condition that is similar to blow-off during engine rapid expansion stroke producing high exhaust unburned hydrocarbon emission. Large thermal stratification has lower heat release rate which is beneficial at high load application while low thermal stratification avoids quenching that benefits low load condition.

2.2. Low Temperature Combustion

Discovery of such combustion mode dated back to as early as 1989 with discovery of combustion with carbon monoxide below 1ppm with negligible NO\(_x\) formation which was initially thought to be malfunction of sensors [5]. Review on low temperature combustion research under different names shares similarities of homogeneous fuel oxidation without development of flame produces extremely low NO\(_x\) and PM emission. This can be achieved by combusting the fuel at special condition by mixing fuel with inert gas, mainly EGR, prior to contact with oxidizer for combustion providing that EGR with reactant temperature are sufficiently high[6]. Such flameless LTC involves strong mixing of exhaust gas recirculation to keep excess air ratio low enough for flameless combustion regime with temperature higher than mixture autoignition point. This can be validate by the methods used to produce flameless combustion conducted with fuel injected into strong EGR zone at high temperature preheated air [7, 6]. The basis for such combustion pollutant emission is to avoid locally rich regions by enhancing pre-combustion mixing and dilution to yield locally low equivalence ratio with EGR to reduce peak combustion temperatures. Similar finding was discovered for diesel spray combustion. As mixture oxygen concentration reduced and combusting the elevated temperature, neither flame luminosity nor OH chemiluminescence is evident. A low temperature reaction took place without any formation of soot. Although such reaction did indicate a slower ignition process, but it still shows certain agreement with apparent heat release rate (AHRR) curves.

3. Proposed Combustion Technology

Limited successes for diesel engine have been reported since as it has strong dependencies on mixture concentration and chemical kinetic [10]. A novel combustion control is proposed based on the hypothesis of direct exhaust gas recirculation injection at high pressure after fuel injection is able to suppress flame development, promoting fuel evaporation and mixing as a mean of combustion control for high efficiency and low pollution LTC diesel engine. Numerical method will be applied together with existing mathematical model to simulate EGR injection parameters to produce desired LTC with OpenFOAM. Parametric optimization will be done using OpenFoam simulation platform which later
compared with experiments as prove of concept and model validation. EGR injection after fuel injection is intended to improve fuel evaporation and mixing promoting LTC to reduce both NOx and soot formation at the same time. Figure 2 is an equivalence ratio versus combustion temperature graph together with nitrogen oxide and soot formation region respectively. Operation of conventional diesel engine falls along the line noted by (a) with ignition taking place at stoichiometric equivalence ratio of 1 forming high temperature flame combustion with thermal NOx and finally ends with extremely rich mixture region entrained in the flame with depleted oxygen producing soot. The proposed method of direct EGR injection is intended to shift the operation of combustion with diffused flame from line (a) to low temperature flameless combustion at line (b). This could possibly be achieved with accurate direct EGR injection timing, amount and duration after fuel injection. Fuel is first allowed to undergo HCCI combustion with excess air and later followed by direct EGR injection to suppress flame development when the mixing reaches stoichiometric ratio. Fuel injection and combustion can continue with high EGR LTC reducing both NOx and soot formation regardless of load condition with high turbulence mixing of LTC chemical kinetic reaction and reduce unburned hydrocarbon by reducing wall wetting at the same time.

4. Conclusion
There has been great interest in LTC and HCCI technology for high efficiency and low pollution emission diesel engine application. However, the application of both combustion modes in diesel engine has limited success due to complex combustion control and narrow engine operation range. The novelty of this research comes from the proposed hypotheses of direct EGR injection as a mean of combustion control to expand the range of engine operation under low temperature flameless combustion mode. This novel combustion method has the potential of alleviating challenges faced by both LTC and HCCI technology making these high efficiency and low pollution emission combustion mode to be successfully implemented to conventional diesel engine with minimal modification.

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