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Thermally Stratified Compression Ignition: A new advanced low temperature combustion mode with load flexibility ☆

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HIGHLIGHTS

- A new advanced low temperature combustion (LTC) mode is introduced: TSCI.
- TSCI uses direct water injection to control heat release in LTC.
- Water injection retards combustion due to the latent heat of vaporization.
- Direct water injection reduces the heat release rate by local evaporative cooling.
- Direct water injection can expand the load range of LTC by more than 350%.

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ABSTRACT

A new advanced combustion mode is introduced, called Thermally Stratified Compression Ignition (TSCI), which uses direct water injection to control both the average temperature and the temperature distribution prior to ignition, thereby providing cycle-to-cycle control over the start and rate of heat release in Low Temperature Combustion (LTC). Experiments were conducted to fundamentally understand the effects of water injection on heat release in LTC. The results show that water injection retards the start of combustion due to the latent heat of vaporization of the injected water. Furthermore, for start of water injection timings between 20 and 70 degrees before top dead center, combustion is significantly elongated compared to without water injection. The 10–90% burn duration with 6.6 and 9.0 mg of water per cycle was 77% and 146% longer than without water injection, respectively. Direct water injection reduces the heat release rate by local evaporative cooling that results in a forced thermal stratification.

Finally, the load limits with and without water injection were determined experimentally. Without water injection, the load range was 2.3–3.6 bar gross IMEP. By using water injection to control heat release, the load range in TSCI was 2.3–8.4 bar gross IMEP, which is a range expansion of over 350%. These results demonstrate that direct water injection can provide significant improvements to both controllability and the range of operability of LTC, thereby resolving the major challenges associated with HCCI.

Abbreviations: aTDC, after Top Dead Center; bTDC, before Top Dead Center; CA50, Crank Angle of 50% burned location; CI, Compression Ignition; CO, Carbon Monoxide; COV, Coefficient of Variation; DI, Direct Injection; EI, Emissions Index; GCI, Gasoline Compression Ignition; GDI, Gasoline Direct Injection; HCCI, Homogeneous Charge Compression Ignition; IMEP, Indicated Mean Effective Pressure; IVC, Intake Valve Closing; LTC, Low Temperature Combustion; Mass PDF, Mass probability density function; MPRR, Maximum Pressure Rise Rate; NOx, Oxides of Nitrogen (NO or NO_2); NVO, Negative Valve Overlap; ORNL, Oak Ridge National Laboratory; PCCI, Premixed Charge Compression Ignition; PFS, Partial Fuel Stratification; PLIF, Planar Laser Induced Fluorescence; PM, Particulate Matter (soot); RCCI, Reactivity Controlled Compression Ignition; SACI, Spark Assisted Compression Ignition; SI, Spark Ignition; SOI, Start of Injection; TSA, Thermal Stratification Analysis; TDC, Top Dead Center; TSCI, Thermally Stratified Compression Ignition; uHC, unburned Hydrocarbon.

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1. Introduction

Low Temperature Combustion (LTC) is a group of advanced combustion concepts that promises simultaneous reductions in fuel consumption and pollutant emissions. Homogeneous Charge Compression Ignition (HCCI) is one of the earliest forms of LTC and possibly the most widely researched [1–6]. In HCCI, a homogeneous mixture of air and fuel is compressed until it autoignites. HCCI therefore pairs the homogenous, ultra-low soot characteristics of conventional well-mixed Spark Ignition (SI) combustion with the high efficiencies (achieved through lean, unthrottled operation) usually typical of diesel Compression Ignition (CI) combustion. Engine-out NOx emissions are kept low through high levels of dilution with air and/or residuals. Due to these factors, HCCI has demonstrated near-zero NOx and soot emissions at efficiencies similar to, or greater than, conventional diesel combustion [5]. However, HCCI is only achievable over a narrow, part-load operating range due to the lack of direct control over the start and rate of heat release. In order to provide control over heat release in HCCI, a better understanding of the fundamental combustion processes is required.

Recently, the community gained a better understanding of LTC heat release through optical chemiluminescence and planar laser-induced fluorescence (PLIF) images, which showed that while HCCI can be compositionally homogeneous, there is a significant amount of thermal stratification (i.e. a distribution of in-cylinder gas temperatures prior to ignition) that stagger the ignition timing of various regions based on their local temperature [7–17]. Depending on the valve strategy and the fuel injection strategy, there can also be compositional gradients of either residual gases or fuel fraction, respectively, that can also stagger the autoignition timing of various regions [18–23]. With this new information, an improved understanding of LTC was achieved: (1) regions autoignite sequentially based on their local temperature and reactivity, and (2) the early-igniting regions release their energy first, compressing the remaining unburned regions causing their subsequent autoignition. Due to this second underlying phenomenon, the energy release process in LTC is a positive feedback loop, which explains its relatively low high-load limit.

In addition to the insight about thermal stratification gained through the PLIF optical diagnostics by Dec and other researchers around the world, a post-processing technique was previously developed and validated by Lawler et al. [24,25] that can estimate an unburned temperature distribution prior to ignition in a fired, metal engine. The technique, called the Thermal Stratification Analysis (TSA), uses isentropic ideal gas relations to model the possible gas temperatures in the cylinder and their change over the compression and combustion processes. The autoignition integral [26] and an ignition delay correlation [27] are then used to predict the ignition timing of each temperature trajectory, which are finally coupled to the calculated heat release characteristics to estimate a temperature distribution. The TSA approach has been previously validated against the optical distributions measured by Dec et al. as well as against CFD simulations [25], and has subsequently been applied to study the effects of wall conditions, engine geometry [28], and operating conditions [29] on thermal stratification. The results showed that wall conditions had a surprisingly small influence on the thermal stratification [28]. Instead, the top dead center (TDC) temperature, combustion phasing, and swirl all had a noticeable influence on the level of thermal stratification prior to ignition [29].

In traditional HCCI, neither the compositional gradients, nor the temperature distribution prior to ignition, nor the positive feedback loop are controlled. This lack of control is responsible for the narrow, part-load operating range. To address the control challenges associated with HCCI, a wealth of alternative LTC modes have been proposed. Reactivity Controlled Compression Ignition (RCCI) uses two distinct fuels and a specific range of direct injection (DI) timings to introduce a gradient of fuel properties in the cylinder prior to ignition [30–33]. By controlling the fraction of each fuel and the DI timing, RCCI has demonstrated the ability to achieve higher loads than pure HCCI with better controllability. However, the requirement of two distinct fuels and fuel systems detracts from RCCI's commercial viability, especially for the light-duty market. Spark Assisted Compression Ignition (SACI) is a variant of HCCI where a spark discharge is used to help control the start and rate of heat release [17,34,35]. In SACI, a flame front burns between 5% and 50% of the mixture, and the remaining 50–95% of the mixture autoignites similarly to pure HCCI. SACI has shown the ability to provide some level of control and help extend the load range. However, the spark discharge introduces a significant amount of variability which can be a challenge for LTC. Gasoline Compression Ignition (GCI) is an advanced combustion concept that uses gasoline in a diesel engine [36,37]. GCI has its advantages, but its NOx emissions and pressure rise rates pose a challenge. Dec et al. introduced Partial Fuel Stratification (PFS) which uses a second injection of fuel during the compression stroke to provide a gradient of equivalence ratios to stagger the ignition timing of various regions when using a φ-sensitive fuel (i.e. a fuel whose autoignition timing is sensitive to variations in equivalence ratio) [21,38].

Most of the alternative LTC modes that attempt to provide control over the start and rate of heat release rely on a direct fuel injection event to introduce a stratification of equivalence ratio and reactivity. This approach can be effective; however, the intentional fuel-air mixture inhomogeneities present a risk of higher particulate matter (PM) and NOx emissions due to the locally rich regions which are closer to the soot production island and have higher burned gas temperatures. In fact, recent detailed particulate emissions measurements on these equivalence-ratio-stratified advanced combustion concepts has shown that although a smoke meter measurement may be zero, the particulate emissions are simply smaller in diameter and different in composition (e.g. increased concentrations of polycyclic aromatic hydrocarbons and aldehydes) [39–44]. This result, in combination with biological research which has shown that smaller particles are more detrimental to human health [45,46], might suggest that the equivalence-ratio-stratified concepts could shift the distribution of particulate matter to a more harmful region compared to conventional diesel combustion.

Instead of attempting to use a forced fuel-air mixture stratification to control the heat release rates in LTC, we propose a new combustion mode that controls the amount of thermal stratification in LTC. This approach, termed Thermally Stratified Compression Ignition (TSCI), employs direct injection of water to control both the mean temperature and the temperature distribution in the cylinder, thereby offering control over the start and rate of heat release in LTC. This paper first presents experimental data to fundamentally understand the effects of the direct water injection event on thermal stratification in the cylinder, and second, presents a load sweep to demonstrate the load limits that are achievable with and without water injection.

Water injection in internal combustion engines has a long history [47–54]. Water injection has been used in SI combustion to mitigate knock [47]. Water injection has also been used to lower temperatures and reduce NOx emissions in any combustion mode [48,49]. Water injection has even been previously investigated in HCCI and Premixed Charge Compression Ignition (PCCI) [50–54]. Specifically, Lund Institute of Technology port injected water and found that the evaporative cooling in the intake manifold allowed