

Reactivity Controlled Compression Ignition (RCCI): A Comprehensive Review of Combustion Fundamentals, Emission Control, Alternative Fuels, and Future Prospects

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Abstract- Reactivity Controlled Compression Ignition (RCCI) is an advanced low-temperature combustion (LTC) strategy that has emerged as one of the most promising solutions to the dual challenge of improving internal combustion (IC) engine fuel efficiency while simultaneously reducing harmful exhaust emissions. Developed at the Engine Research Center (ERC), University of Wisconsin-Madison, RCCI exploits in-cylinder fuel blending of a low-reactivity fuel (LRF) and a high-reactivity fuel (HRF) to create a stratified charge that autoignites progressively from high-reactivity zones outward, enabling precise combustion phasing control. This paper presents a comprehensive review of RCCI combustion technology spanning its foundational principles, thermodynamic advantages, fuel pairing strategies, and parametric effects of operating variables such as exhaust gas recirculation (EGR), injection timing and pressure, premixed ratio, and compression ratio. The review critically analyses combustion characteristics, emission profiles, and thermal efficiencies achievable across a wide operating range, and covers the role of alternative fuels including ethanol, methanol, natural gas, hydrogen, and ammonia. Special emphasis is placed on challenges limiting RCCI's commercial deployment—elevated HC and CO emissions, restricted high-load range, and complex control requirements—as well as Indian research contributions from IIT Bombay and IIT Madras. The paper concludes with future research directions encompassing machine learning-aided control, hybrid electrification integration, and zero-carbon fuel pathways.

Keywords: Reactivity Controlled Compression Ignition, Dual Fuel Combustion, Low Temperature Combustion, NO_x, Soot, EGR, Alternative Fuels, Emission Reduction, Thermal Efficiency, HCCI, PCCI

I. INTRODUCTION

The internal combustion engine (ICE) has served as the cornerstone of global transportation for over a century. Despite its technological maturity, the ICE

faces mounting pressure from stringent emissions regulations (Euro VI, BS-VI, EPA Tier 4) and the urgent need to improve fuel economy. Conventional compression ignition (CI) diesel engines, while offering high thermal efficiency and robustness, produce significant quantities of nitrogen oxides (NO_x) and particulate matter (PM), whose simultaneous reduction has long been constrained by the well-documented NO_x–soot trade-off.

To circumvent this trade-off, researchers have investigated Low Temperature Combustion (LTC) strategies. These share the common goal of achieving distributed, premixed ignition at temperatures sufficiently low to suppress NO_x formation while avoiding locally rich diffusion-burn regions responsible for soot. The most prominent LTC strategies include Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI).

The seminal work of Kokjohn et al. (2011) at the University of Wisconsin-Madison demonstrated that RCCI combustion could achieve a peak gross indicated thermal efficiency of 56% while simultaneously reducing NO_x by three orders of magnitude and soot by a factor of six compared to conventional diesel combustion (CDC). These results generated immense enthusiasm and catalysed a global research effort spanning academic institutions, national laboratories, and the automotive industry.

II. BACKGROUND: EVOLUTION OF LOW TEMPERATURE COMBUSTION

2.1 Limitations of Conventional Combustion

Conventional diesel combustion (CDC) operates in a diffusion-controlled mode where fuel is injected near top dead centre (TDC) and immediately ignites. The locally fuel-rich regions give rise to soot formation, while peak in-cylinder temperatures exceeding 2000 K drive thermal NO_x formation via the extended Zeldovich mechanism. After-treatment devices (DOC, DPF, SCR) add cost, weight, and back-pressure penalties.

2.2 HCCI, PCCI, and the Emergence of RCCI

HCCI combustion achieves very low NO_x and soot by premixing fuel uniformly with air before compression. However, combustion phasing cannot be directly controlled, and excessive pressure rise rates (PRR) at high loads limit its operating range. PCCI extended HCCI's range by injecting fuel early in the compression stroke, but early injection of diesel resulted in poor vaporisation, wall wetting, and elevated HC/CO emissions.

RCCI was conceived by Kokjohn et al. (2009–2011) to address these limitations. By introducing a small amount of a high-reactivity fuel (HRF, e.g., diesel) into a background of well-premixed low-reactivity fuel (LRF, e.g., gasoline), a controlled reactivity stratification is created inside the cylinder. This stratification serves as the primary combustion control mechanism, enabling sequential autoignition that spreads from high-reactivity zones to lower-reactivity regions.

Table 1: Comparative Overview of Combustion Strategies

Attribute	CDC	HCCI	PCCI	RCCI
NO _x Emissions	High	Very Low	Low	Very Low
Soot/PM	High	Very Low	Low–Med	Very Low
HC & CO	Low	High	Med–High	Med–High
Thermal Efficiency	40–42%	>50%	44–48%	50–56%
Combustion Control	Good	Very Poor	Moderate	Good
Fuel Flexibility	Low	Low	Low	High

III. FUNDAMENTALS OF RCCI COMBUSTION

3.1 Operating Principle

The RCCI strategy is based on in-cylinder fuel blending to establish a controlled reactivity gradient before autoignition. The operational sequence occurs in three stages: (1) Charge Preparation — the LRF is injected into the intake port via a port fuel injector (PFI) to create a well-homogenised mixture; (2) Reactivity Stratification — the HRF is directly injected (DI) before TDC using the common-rail system, creating regions of elevated local reactivity; (3) Sequential Autoignition — as the piston approaches TDC, autoignition occurs first in HRF-rich regions, then propagates outward into LRF-rich zones in a controlled manner.

3.2 Thermodynamic Efficiency Advantages

RCCI achieves significantly higher thermal efficiencies than CDC for two principal reasons. First, the premixed, low-temperature combustion reduces heat transfer losses: the absence of a high-temperature diffusion flame lowers mean charge temperature and wall heat flux substantially. Second, the nearly constant-volume nature of premixed autoignition (compared to CDC's extended diffusion-burn period) brings the thermodynamic cycle closer to the ideal Otto cycle. Indicated efficiencies as high as 59% have been demonstrated using E85-diesel RCCI in a heavy-duty research engine at the Wisconsin ERC.

3.3 Key Performance Metrics

Performance assessment uses the following parameters: Gross Indicated Thermal Efficiency (GITE) — RCCI consistently demonstrates values 8–16% higher than equivalent CDC; Pressure Rise Rate (PRR) — must remain below 8–10 bar/deg to maintain acceptable noise and structural integrity; Crank Angle of 50% burn (CA50) — maintained near 5–8° ATDC for optimal efficiency; and Combustion Efficiency (η_c) — the fraction of fuel energy chemically released, accounting for CO and HC losses.

IV. FUEL COMBINATIONS IN RCCI ENGINES

RCCI's most significant advantage over prior LTC strategies is its fuel flexibility. Key pairings studied in literature are summarised below.

4.1 Gasoline-Diesel (Benchmark)

The gasoline-diesel pairing is the most extensively studied RCCI combination. Kokjohn et al. documented NO_x reductions of three orders of magnitude and soot reductions by a factor of six relative to CDC, with a 16.4% increase in gross indicated efficiency. The E85-diesel variant achieved indicated efficiencies approaching 59%, benefiting from ethanol's higher latent heat of vaporisation and reduced soot precursors.

4.2 CNG-Diesel

CNG as LRF is highly attractive for heavy-duty applications given growing infrastructure. Research at IIT Bombay (Khedkar et al., 2024) demonstrated approximately 62% reduction in NO_x and 36% reduction in soot relative to CDC over the WLTC drive cycle, with fuel economy of 21.6 km/l (diesel equivalent). Methane slip remains a challenge requiring oxidation catalysts.

4.3 Alcohol-Based RCCI (Methanol, Ethanol, n-Butanol)

Methanol and ethanol (RON ≈ 109) offer high octane numbers, high latent heat of vaporisation, and renewable production pathways. Ethanol-biodiesel RCCI has shown soot reductions of 80–90% and NO_x reductions of 70–95% relative to CDC. n-Butanol's higher energy density (~36 MJ/kg) and infrastructure compatibility make it a practical alternative; a 2025 study (Scientific Reports) found optimised n-butanol/gasoline-biodiesel blends achieving lowest NO_x at 150 ppm at 2800 rpm.

4.4 Ammonia and Hydrogen (Zero-Carbon)

The drive toward zero-carbon combustion has stimulated interest in ammonia (NH₃) and hydrogen (H₂) as RCCI LRFs. Numerical investigations (Xu and Bai, 2024) demonstrated RCCI operation with up to 50% ammonia energy substitution with pilot diesel, though with elevated NO emissions. Hydrogen addition improves combustion efficiency

through higher flame speed. These pairings produce essentially zero soot and CO₂ but require careful NO_x management.

Table 2: Comparative Performance of RCCI Fuel Combinations

LRF / HRF	Max ITE	NO _x Red.	Soot Red.	HC/CO	Load Range
Gasoline / Diesel	~56 %	~1000×	~6×	Elevated	Moderate
E85 / Diesel	~59 %	Very High	Very High	Elevated	Moderate
CNG / Diesel	~50–53%	High	Very High	Moderate	Moderate
Methanol / Diesel	~50–55%	Very High	High	Elevated	Moderate
n-Butanol / Biodiesel	~44–48%	High	High	Variable	Limited
NH ₃ +H ₂ / Diesel	~42–48%	Moderate *	Zero	N/A	Limited

V. EFFECTS OF OPERATING PARAMETERS & EMISSION CHARACTERISTICS

5.1 Key Operating Parameters

Premixed Ratio (PR): The fraction of total fuel energy provided by the LRF is the most critical RCCI control parameter. Optimal PR for most gasoline-diesel RCCI operations lies between 60–80%. At medium loads (6–9 bar IMEP), PR ≈ 70% typically balances thermal efficiency, PRR, NO_x, soot, HC, and CO simultaneously within acceptable limits.

Injection Timing & EGR: Direct injection timing is the primary combustion phasing actuator. Advanced SOI increases mixing time and retards CA₅₀; retarded SOI creates steeper reactivity gradients and advances CA₅₀. EGR is essential for extending the high-load operating range — approximately 50% EGR may be required at high loads. Cooled EGR

yields lower PRR and NO_x compared to hot EGR, though at the expense of higher THC emissions.

Compression Ratio (CR): CR values of 14:1–16:1 (lower than typical diesel CR of 17:1–20:1) improve the RCCI operating range by moderating peak PRR. Higher injection pressure improves HRF atomisation and combustion efficiency but can increase NO_x emissions.

5.2 Emission Characteristics

NO_x Emissions: RCCI's premixed, low-temperature heat release maintains charge temperatures well below the 1800 K thermal NO_x threshold. Kokjohn et al. (2011) reported NO_x reductions of approximately 1000× relative to CDC — gasoline-diesel RCCI at 9 bar IMEP produced only ~0.002 g/kWh, far below the Euro VI limit of 0.4 g/kWh.

Soot/PM: By pre-mixing the LRF homogeneously and injecting a small HRF fraction well before TDC, RCCI substantially reduces fuel-rich zones. Soot reductions of 80–90% are achievable with alcohol-biodiesel pairings; ammonia/hydrogen LRFs produce essentially zero soot.

HC and CO: The principal emission trade-off in RCCI is elevated HC and CO relative to CDC, arising from incomplete combustion of premixed LRF in low-temperature crevice regions. RCCI HC emissions consistently exceed 9 g/kWh for gasoline-diesel pairings — far above the Euro VI limit of 0.13 g/kWh — necessitating DOC after-treatment. Low RCCI exhaust temperatures (often below 250°C) impair DOC light-off efficiency, making thermal management a critical enabler for commercial deployment.

Table 3: RCCI Engine-Out Emissions vs. Euro VI Limits

Pollutant	Euro VI Limit (g/kWh)	Typical CDC (g/kWh)	Typical RCCI (g/kWh)
NO _x	0.40	2.0–4.0	0.002–0.05
PM	0.01	0.05–0.15	< 0.005
HC	0.13	0.05–0.2	2.0–12.0*
CO	1.50	0.5–1.5	2.0–20.0*

*Requires DOC after-treatment for regulatory compliance

VI. COMPUTATIONAL STUDIES, CONTROL & INDIAN RESEARCH

6.1 CFD and Numerical Modelling

CFD simulations have been indispensable for understanding RCCI's spatial fuel stratification, turbulent spray-air interaction, and multi-component autoignition kinetics. CONVERGE CFD (Convergent Science) is widely adopted due to its automated mesh generation, adaptive mesh refinement, and integrated chemical kinetics solver. For gasoline-diesel RCCI, primary reference fuel (PRF) mechanisms for n-heptane and iso-octane are extensively used; for ammonia-diesel, dedicated NH₃/n-heptane mechanisms validated against rapid compression machine data have been developed.

Multi-zone models offer computationally efficient alternatives for control-oriented applications, discretising the combustion chamber into 10–15 thermochemical zones. These models predict in-cylinder pressure within cycle-to-cycle variation bounds and are suitable for hardware-in-the-loop (HIL) simulation.

6.2 Combustion Control Strategies

RCCI combustion control is one of the most significant barriers to commercialisation. CA50 and IMEP are simultaneously influenced by PR, SOI, EGR rate, injection pressure, intake temperature, and boost pressure. Model Predictive Control (MPC) has been identified as the most promising approach for RCCI's multi-input, multi-output (MIMO) system with explicit constraints on PRR and peak cylinder pressure. Dual-mode RCCI-CDC operation requires seamless switching between RCCI at part-load and conventional diesel combustion at high load, with careful EMS calibration to avoid emission spikes during mode transitions.

6.3 Indian Research Contributions

IIT Bombay (Prof. Asish Kumar Sarangi's group): Key publications include vehicle duty cycle assessments over the WLTC using AVL CRUISE for gasoline-diesel and CNG-diesel RCCI-CDC dual combustion mode engines (Khedkar et al., ASME ICEF2024), and studies on EGR effectiveness at low-load (SAE International Journal of Fuels and Lubricants, 2022). The group collaborates

internationally with Prof. Jose Martin Herreros at the University of Birmingham, UK.

IIT Madras – NCCRD: The National Centre for Combustion Research and Development, supported by the SERB-DST, hosts one of the world's largest academic combustion research facilities with over 30 faculty members. NCCRD actively collaborates with Mahindra, TVS, Cummins, AVL, and GAIL on advanced combustion technologies.

Anna University: Prof. Ganesh Duraisamy, supported by DST-CERI (2016–2019), developed a methanol-diesel RCCI engine in partnership with Ashok Leyland, demonstrating a viable pathway for RCCI adoption in India's commercial vehicle sector.

VII. CHALLENGES, FUTURE PROSPECTS & CONCLUSION

7.1 Key Challenges

The principal challenges limiting RCCI commercialisation are:

- **Elevated HC/CO Emissions:** Arising from incomplete combustion in low-temperature crevice volumes and squish regions. DOC after-treatment is required but impaired by RCCI's characteristically low exhaust temperatures (often below 200°C at light loads).
- **Limited High-Load Range:** The premixed nature of RCCI leads to excessive PRR at high loads, typically restricting operation to approximately 60–75% of peak engine load.
- **Hardware Complexity:** RCCI requires supplementary PFI hardware, additional fuel storage systems, and sophisticated dual-fuel engine management software.
- **Cold-Start and Low-Load Operation:** Insufficient charge temperatures lead to misfire risk, requiring special start-up strategies including reduced PR and intake air preheating.
- **After-Treatment Compatibility:** Low RCCI exhaust temperatures create challenges for SCR, DPF, and DOC systems, requiring active thermal management strategies.

7.2 Future Research Directions

Machine Learning and AI: ANNs, support vector machines, and deep reinforcement learning (DRL) are being applied to create fast surrogate models for real-time MPC, enabling autonomous optimisation across a wide operating range without explicit calibration tables.

RCCI in Hybrid Electric Vehicles: Integration with HEV/PHEV platforms allows the RCCI engine to operate predominantly in its optimal efficiency range, with the electric motor handling transient demands and urban low-speed operation. A review identified PHEVs with RCCI engines as having substantial potential to reduce both local (NO_x, PM) and global (CO₂) emissions.

Zero-Carbon and Renewable Fuels: E-fuels (synthetic methanol, dimethyl ether, synthetic gasoline) produced from renewable electricity and captured CO₂ can be designed with tailored octane/cetane properties for RCCI. Green hydrogen and green ammonia offer carbon-free pathways, with ongoing research at IIT Madras and Anna University on biomass-derived fuel behaviour in RCCI mode.

Marine and Heavy-Duty Applications: Natural gas-diesel RCCI in marine diesel engines delivers lower NO_x (meeting IMO Tier III standards) and significantly reduced PM without expensive SCR systems. Heavy-duty truck RCCI programs evaluated at Oak Ridge (ORNL) and Argonne National Laboratories (ANL) have shown encouraging results for CNG-diesel and E85-diesel RCCI in Class 8 trucks.

7.3 Conclusion

Reactivity Controlled Compression Ignition represents a technically elegant and thermodynamically powerful combustion strategy that addresses the fundamental limitations of both conventional diesel combustion and earlier LTC concepts. The key findings from this review are:

- RCCI achieves gross indicated thermal efficiencies of 50–59%, substantially exceeding the 40–42% typical of CDC at equivalent operating conditions.

- NO_x reductions of up to three orders of magnitude and soot reductions by a factor of six or more are achievable relative to CDC, enabling near-Euro VI compliance without SCR in many operating conditions.
- A wide range of fuel pairings—gasoline-diesel, CNG-diesel, ethanol-diesel, methanol-diesel, n-butanol-biodiesel, hydrogen-diesel, and ammonia-diesel—are viable, providing flexibility for diverse energy supply chains.
- Elevated HC and CO emissions remain the primary regulatory challenge, requiring DOC after-treatment and thermal management to ensure catalyst light-off.
- Indian institutions, particularly IIT Bombay and IIT Madras (NCCRD), have made significant contributions to RCCI research through vehicle duty cycle assessments, EGR effectiveness studies, and industry-partnered engine development.

The path to commercial RCCI deployment requires addressing the remaining challenges of limited high-load range, HC/CO after-treatment, dual-fuel system complexity, and robust transient combustion control. Integration of RCCI with hybrid electric powertrains, machine learning-based control systems, and renewable fuel infrastructure represents a compelling vision for next-generation high-efficiency, ultra-low-emission propulsion systems.

VIII. ACKNOWLEDGEMENTS

The author acknowledges the pioneering contributions of the Engine Research Center (ERC) at the University of Wisconsin-Madison, particularly Prof. Rolf D. Reitz, Dr. Scott Kokjohn, Dr. Derek Splitter, and Dr. Reed Hanson. Gratitude is also extended to the research groups at IIT Bombay (Prof. Asish Kumar Sarangi) and IIT Madras (NCCRD, Prof. Satyanarayana Chakravarthy) for their sustained contributions to RCCI research within the Indian academic context.

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