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Ph.D. Seminar Talk 2

Title: **Development and engine characterization of an ammonia-diesel dual-fuel CRDI diesel engine, and enhancement of performance and combustion using advanced injection strategies and hydrogen addition.**

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Date and Time: **08-04-2026 @ 3:00 PM**

Venue: **Rudolf Diesel Hall, First Floor, IC Engines Laboratory**

Abstract

Ammonia is increasingly recognized as a promising carbon-free fuel and hydrogen energy carrier for future compression ignition (CI) engine applications because of its established storage and transportation infrastructure and its potential for reducing greenhouse gas emissions. Compared to hydrogen, ammonia offers easier storage and higher volumetric energy density, making it attractive for stationary power generation and heavy-duty engine applications. However, the direct utilization of ammonia in CI engines remains challenging because of its low laminar flame speed, high auto-ignition temperature, and slower combustion kinetics, which lead to delayed combustion, lower thermal efficiency, and unstable operation. Therefore, advanced combustion strategies are required to improve ammonia utilization in diesel engines.

The present research focuses on the comprehensive experimental and computational investigation of ammonia-diesel dual-fuel (ADDF) combustion in a twin-cylinder common rail direct injection (CRDI) diesel engine. A multi-gas fuel-flexible engine setup was developed to enable controlled induction of ammonia and hydrogen into the intake manifold while maintaining diesel direct injection through the CRDI system. The developed setup includes independent gas supply lines, pressure regulation systems, anti-corrosive flow control arrangements, blending chambers, and real-time electronic control of diesel injection parameters. Experiments were primarily conducted at 1800 rpm and 24 Nm load, corresponding to a brake mean effective pressure (BMEP) of approximately 3.32 bar. This operating condition was selected because medium-load operation represents a practically relevant regime for stationary power applications, where engines operate for a significant portion of their duty cycle.

Initially, experimental investigations were carried out to evaluate the influence of ammonia energy share (AES) on engine performance and combustion characteristics under ADDF

operation. Ammonia flow rates up to 40 SLPM were achieved, corresponding to nearly 47% AES at a DIT of 23.4 CAD BTDC. Beyond this operating limit, the coefficient of variation (COV) of IMEP exceeded the selected combustion stability threshold of 3%, indicating a noticeable increase in cycle-to-cycle combustion variability at higher ammonia substitution levels. At the selected medium-load condition (BMEP ≈ 3.32 bar), diesel-only operation achieved a brake thermal efficiency (BTE) of approximately 25.5%, whereas pure ADDF operation at 47% AES reduced the BTE to nearly 23.3% due to ammonia's lower reactivity, higher specific heat capacity, and delayed combustion development. However, CFD analysis revealed that higher ammonia substitution promoted comparatively more homogeneous ammonia–air mixture formation and increased local regions near stoichiometric equivalence ratio, which accelerated the main combustion phase and reduced combustion duration (CA10-CA90) from 15.5 CAD (diesel-only) to 12.8 CAD at 47% AES. Simulation results further indicated enhanced consumption of H2 radicals and at higher ammonia shares, supporting improved propagation of ammonia oxidation reactions.

To overcome the reduction in thermal efficiency observed under pure ADDF operation, two combustion enhancement strategies were subsequently explored. The first strategy involved hydrogen enrichment of the ADDF mixture to improve in-cylinder reactivity, accelerate ammonia oxidation, and enhance combustion completeness. The second strategy focused on optimization of diesel injection characteristics under pure ADDF operation through variation of diesel injection timing (DIT) and advanced split injection strategies involving pilot and main injections. These approaches were aimed at improving combustion phasing, ignition stability, heat release characteristics, and overall engine performance while maintaining stable high-ammonia operation.

Building upon the baseline ADDF investigations, hydrogen enrichment was introduced as the first combustion enhancement strategy to improve ammonia oxidation and recover the efficiency loss associated with high ammonia substitution. Experiments were conducted at a fixed ammonia flow rate of 40 SLPM (≈47–50% AES) and a constant main diesel injection timing of 23.4 CAD BTDC, while hydrogen flow rate was varied from 0 to 10 SLPM. The addition of hydrogen enhanced in-cylinder mixture reactivity due to its low ignition energy, high flame speed, and strong radical generation capability (H, O, and OH radicals), which promoted faster ammonia decomposition and combustion. Consequently, BTE improved progressively from approximately 23.3% in pure ADDF operation to nearly 24.8% at 7% hydrogen energy share (HES), while combustion duration reduced and CA50 advanced toward more favorable combustion phasing. CFD analysis further revealed enhanced OH radical formation and more uniform ammonia consumption under hydrogen-enriched conditions, indicating accelerated combustion kinetics and improved combustion completeness. Emission analysis showed that ammonia substitution significantly reduced CO2 emissions, while hydrogen enrichment further reduced NH3 slip and N2O emissions due to improved oxidation characteristics. However, NOx emissions increased at 7% HES because of elevated in-cylinder temperatures and enhanced thermal NO formation.

The second strategy involved optimization of diesel injection characteristics under pure ADDF operation through two independent approaches: (i) systematic variation of diesel injection timing (DIT), and (ii) advanced split diesel injection strategies involving pilot and main injections. In the first approach, the DIT was varied from 10 to 46 CAD BTDC at nearly 47% AES and a medium-load condition (BMEP ≈ 3.32 bar). Advancing the DIT improved mixture preparation, combustion phasing, and ammonia oxidation, with the optimum performance achieved at 36 CAD BTDC where the BTE improved to approximately 24.3%. Advanced injection timings also reduced combustion noise and improved emission characteristics due to smoother heat release and enhanced in-cylinder homogeneity. In the second approach, split injection strategies were experimentally and numerically investigated near 47% AES to further improve combustion stability and efficiency. Among the investigated cases, the optimum split strategy consisting of a 20% pilot injection ratio (PIR) with pilot injection at 60 CAD BTDC and main injection at 36 CAD BTDC achieved a combustion efficiency of nearly 95% and improved BTE to approximately 25%, while maintaining stable operation with COV of IMEP below 3%. CFD analysis further revealed enhanced OH radical formation and improved mixture homogeneity under the optimized split strategy, confirming accelerated ammonia oxidation and more controlled heat release characteristics.

Complementary CFD simulations using CONVERGE software were performed throughout the study to support the experimental investigations and provide deeper insight into in-cylinder combustion phenomena. The CFD model was validated against experimentally measured in-cylinder pressure and heat release rate profiles for diesel-only, ADDF, and hydrogen-enriched ADDF conditions. The simulations provided detailed understanding of fuel-air mixing, ignition behavior, heat release evolution, ammonia oxidation pathways, and OH radical distribution. The numerical results showed that optimized injection strategies and hydrogen enrichment enhanced radical formation and accelerated ammonia oxidation, resulting in more homogeneous combustion and improved energy release characteristics.

Overall, the present research establishes a comprehensive experimental and computational framework for ammonia–hydrogen–diesel combustion in CRDI engines through integrated investigations on ammonia substitution, hydrogen enrichment, diesel injection timing optimization, split injection strategies, combustion noise analysis, and CFD-based combustion modelling. The findings demonstrate that both optimized diesel injection strategies and hydrogen-assisted combustion independently contribute toward improving combustion stability, ammonia utilization, thermal efficiency, and emissions performance under medium-load operation. The study highlights the strong potential of ammonia as a low-carbon fuel for stationary power applications while identifying practical pathways to overcome its inherent combustion limitations. Future work will focus on the combined optimization of ammonia–hydrogen–diesel combustion over a wider range of engine loads and speeds, including transient operating conditions, advanced split injection strategies, and suitable exhaust after-treatment systems to simultaneously improve combustion stability, thermal efficiency, and emissions characteristics.