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Experimental Investigation of Combustion and Emission Characteristics of a Heavy-duty Direct-injection Hydrogen Engine with Active and Passive Jet Ignition

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Abstract

Hydrogen internal combustion engines offer a promising pathway toward carbon-free transportation. Compared to conventional spark ignition systems, jet ignition technology can significantly improve combustion stability and thermal efficiency while reducing emissions. However, systematic experimental studies on jet-ignited hydrogen engines—especially those comparing active and passive pre-chamber configurations—remain scarce. This study aims to experimentally investigate the combustion and emission characteristics of a heavy-duty, direct-injection hydrogen engine equipped with a jet ignition system, operating under both active (fuel-supplied pre-chamber) and passive (non-fueled pre-chamber) modes.A single-cylinder heavy-duty hydrogen engine with a central pre-chamber jet ignition system was tested at a constant speed of 1000 rpm and an indicated mean effective pressure (IMEP) of 10 bar. Three key control parameters were varied: spark timing, excess air ratio (λ, ranging from 1.6 to 2.8), and pre-chamber fuel energy ratio (0–5%). Cylinder pressure, hydrogen flow rate, and exhaust emissions were measured over 200 consecutive cycles to evaluate combustion phasing (CA10, CA50, CA90), indicated thermal efficiency (ITE), cycle-to-cycle variation (COV IMEP), NOx, and unburned hydrogen emissions. Results show that spark timing primarily shifts combustion phasing in both modes, with negligible effect on combustion duration. Advancing spark timing leads to earlier CA50 and higher peak pressures. The maximum ITE is achieved when CA50 is near 7°CA ATDC for both modes, though active mode requires less spark advance due to stronger ignition energy. Increasing λ prolongs combustion duration but drastically reduces NOx emissions; at $\lambda \geq 2.4$, NOx approaches near-zero levels. However, active mode exhibits a higher risk of pre-ignition under ultra-lean conditions. The pre-chamber fuel energy ratio has a minor effect on combustion phasing but significantly increases NOx and reduces ITE, suggesting that minimal fueling of the pre-chamber is preferred.In conclusion, jet ignition effectively enhances combustion in heavy-duty direct-injection hydrogen engines. The active mode provides higher ignition energy and faster combustion but at the cost of increased NOx and abnormal combustion risk. For optimal trade-offs, $\lambda \approx 2.6$ and minimal pre-chamber fueling are recommended.

Keywords

Hydrogen Engine, Pre-chamber, Jet Ignition, Direct Injection, Combustion Characteristics