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Performance Analysis of an Onboard Floating Piston Hydrogen Compressor for High-Pressure Direct Injection Commercial Vehicles Across Driving Cycles

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Abstract

Transitioning to hydrogen-fueled direct-injection internal combustion engines in long-haul trucks offers a near-term pathway to near-zero greenhouse gas emissions from this economically critical sector. High-pressure direction injection (HPDI) can achieve diesel-like performance and efficiency but requires hydrogen pressures of 28 MPa or higher at the fuel injectors. With onboard compressed hydrogen storage, fuel tank pressure decreases as hydrogen is consumed, often dropping below this threshold, leaving significant amounts of fuel unused. Analysis indicates that in a 70 MPa onboard hydrogen storage system, nearly 50% of the fuel remains inaccessible due to insufficient pressure.

This study introduces an onboard hydraulically driven hydrogen gas booster system to address the challenge of maintaining the required injection pressure for HPDI technology at low storage tank pressures. This system ensures sustained injection pressure throughout vehicle operation. A thermodynamic model incorporating real gas effects was developed and validated using experimental data from a prototype testing facility designed and instrumented for this purpose. Key parameters for hydrogen and natural gas compression are compared. The simulation results indicate that assuming ideal gas behavior leads to an underestimation of compressor size and power requirements for hydrogen compression, whereas the opposite trend is observed for methane (CH_4). The compressor's performance is analyzed in an HPDI-equipped internal combustion engine vehicle, evaluating fuel storage from full capacity (70 MPa for compressed hydrogen and 25 MPa for compressed natural gas) down to lower storage pressures across typical truck driving cycles. Key performance indicators, including compression work, efficiency, and fuel utilization, are assessed to determine the feasibility of onboard hydrogen compression.

The modelled results demonstrate that while the compressor enhances hydrogen utilization and extends vehicle range, it imposes a significant parasitic load on the HPDI engine. In contrast, a natural gas compressor is an essential component for CNG HPDI throughout the entire driving cycle, yet its parasitic load on the engine is approximately four times lower than that of a hydrogen compressor operating at the same pressure ratio and delivering the same fuel energy content. This study further highlights how careful management of tank pressure across different drive cycles can minimize losses and improve overall system efficiency for H_2 HPDI. Additionally, by evaluating compressor performance in real-world driving conditions, opportunities for design and control optimizations are identified. This research advances the feasibility of onboard hydrogen compression for HPDI engines in heavy-duty applications, contributing to the development of sustainable long-haul transportation.