Mixed Electrochemical/Combustion Energy Conversion for High-Efficiency, Small-Scale Engines

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Motivation

Data gathered by DOE in the EIA Energy Review shows that there are significant gains to be made in improving energy efficiency in the transportation and electricity generation sector.

System Concepts

Low-Temperature Architecture

The low-temperature system couples a homogeneous charge compression ignition (HCCI) piston engine operating at a fuel-rich equivalence ratio with a high-temperature polymer electrolyte membrane (HTPEM) fuel cell. The system uses a water-gas shift reactor before the HTPEM to shift the gas to a more hydrogen rich composition and a conventional oxidation catalyst (COC) to react any remaining fuel leaving the fuel cell.

High-Temperature Architecture

The high-temperature system couples a fuel-rich direct-injection, low heat rejection (Di-LHR) piston engine with a solid-oxide fuel cell (SOFC). The system is also boosted to a pressure of 5 bar by a turbocharger, with the turbine coupled to a generator for additional work extraction. Similar to the low temperature case, a catalytic reformer precedes the fuel cell to shift bond energy into more hydrogen and a catalytic afterburner (CAB) follows to react any remaining fuel. There is also a secondary fuel stream into the fuel cell that undergoes internal reforming to provide more fuel for additional work extraction.

High-Temperature Architecture w/ Added Steam Cycle

To push towards higher efficiencies in the high-temperature architecture, a steam cycle was added to extract the remaining thermal exergy from the exhaust stream. This system also uses the excess heat transfer from the fuel cell to superheat the steam for additional work extraction.

Results

Low-Temperature Architecture

The modeling results from the low temperature system show an increase in overall efficiency and a decrease in the exergy destroyed due to combustion. It is important to note, though, that the combustion destruction is combined with the other losses due to reaction (i.e., the fuel cell loss and the reactor losses), the overall exergy destruction due to reactions is actually greater in the combined system than the combustion destruction alone in the HCCI base case.

High-Temperature Architectures

The initial high temperature architecture (LHR-SOFT) shows a significant increase in efficiency over the turbo-compounded LHR engine. Additionally, the overall destruction due to reactions has been decreased. There is still a sizable amount of exergy available in the exhaust, though. When the steam cycle is added, this exhaust loss is drastically decreased, and the efficiency surpasses 60%. In exploring how this architecture could reach 70% exergy efficiency, the work contribution by the fuel cell to the overall system was increased to 10% that of the engine by increasing the amount of secondary fuel added. This resulted in decreased heat transfer losses due to the endothermic internal reforming reactions as well as increased overall work output, leading to an overall efficiency of 69%.

Conclusions

• Coupling a piston engine with a fuel cell can reduce the overall exergy destruction due to reactions, thereby opening a path to efficiencies greater than those possible with piston engines alone.
• Shifting more chemical conversion into the fuel cell and away from combustion can further increase the overall efficiency.
• Moving from a combustion-based system to a mixed combustion/electrochemical system is not inherently a better approach. The combined reaction losses of the mixed system may be greater than the combustion losses in the solely combustion-based system.
• Excess thermal exergy and how to manage it remains a challenge in the mixed electrochemical/combustion system.