Use of mixed combustion/electrochemical energy conversion to achieve efficiencies in excess of 70% for transportation-scale engines

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Abstract

Improving engine efficiency serves to simultaneously increase energy resource utilization and reduce greenhouse gas emissions. Large-scale engine systems used for centralized electricity generation are relatively efficient, but small-scale engines used for distributed generation and transportation are still rather inefficient. The goal of this research is to design an energy conversion system capable of realizing high efficiencies at a smaller scale suitable for distributed generation and transportation.

Our design for such an engine system is guided by exergy analysis. Past work in our lab has shown that in order to achieve ultra high efficiencies, it is necessary to reduce the exergy lost to combustion. We address this loss by utilizing a fuel cell to complement an internal combustion engine in a combined-cycle system that realizes high efficiency.

We are in the midst of exploring both a high-temperature and low-temperature approach to a mixed electrochemical/combustion system. Preliminary modeling results of the high-temperature approach indicate an exergy efficiency of 63% (65% LHV) and we are working to manage operating parameters and device integration to increase this number further. As our proposed system includes using devices in unconventional operating regimes, we are also developing experimental capabilities to validate our models where there is uncertainty in device performance.

Future efforts include modeling a proposed low-temperature approach, implementing a gas chromatograph to characterize gas composition throughout the system, and using rich-combustion products from an engine to power a high-temperature PEM fuel cell. Through our combined modeling and experimental work, we hope to demonstrate a system with greater than 70% efficiency (LHV) at a scale suitable for distributed generation and transportation.

Introduction

As worldwide demand for energy services increases and global-mean temperatures continue to rise, it is necessary to develop engines that both make effective use of energy resources and minimize resulting greenhouse gas emissions. Increasing engine efficiency achieves both of these goals simultaneously. By making more effective use of an input resource, high-efficiency engines use less fuel to produce a unit of work and therefore emit fewer greenhouse gases than their less efficient counterparts.

Large-scale engines that produce between 10 and 500 MW of power for centralized electricity generation are currently capable of realizing 60% efficiency (LHV) [1]. Small-scale engines that produce between 100 kW and 10 MW of power for distributed electricity generation and transportation, however, are only 25-50% efficient on an LHV basis [2, 3]. Of the engines used in distributed generation and transportation, piston engines dominate, as gas turbines of such a small size are significantly less efficient than their larger counterparts. Fuel cells are also used at this scale but are impeded by cost, low efficiency at high load, and stringent fuel requirements.

The goal of this research is to develop a highly efficient, distributed generation- and transportation-scale engine system by combining a piston engine and a fuel cell. Our decision to use these two technologies together stems from previous work that showed that even the most advanced IC engine configurations cannot achieve exergy efficiencies higher than 60% [4]. This decision is further motivated by the complementary nature of IC engines and fuel cells.

Pushing Past 60% Efficiency: Exergy Loss due to Combustion

Past members of our lab have thoroughly investigated the operation of piston engines for high efficiency and have analyzed conventional IC engines as well as proposed advanced systems that do not yet exist commercially. Figure 1a shows the results of an exergy analysis of two modern transportation engines—a spark-ignited gasoline engine and a turbo-charged Diesel engine of comparable output—while Figure 1b shows the results of an exergy analysis of three low-heat-rejection (LHR) engines with turbocharging and turbo-compounding—a base case, an engine with steam injection, and an engine with a Rankine bottoming cycle [4].

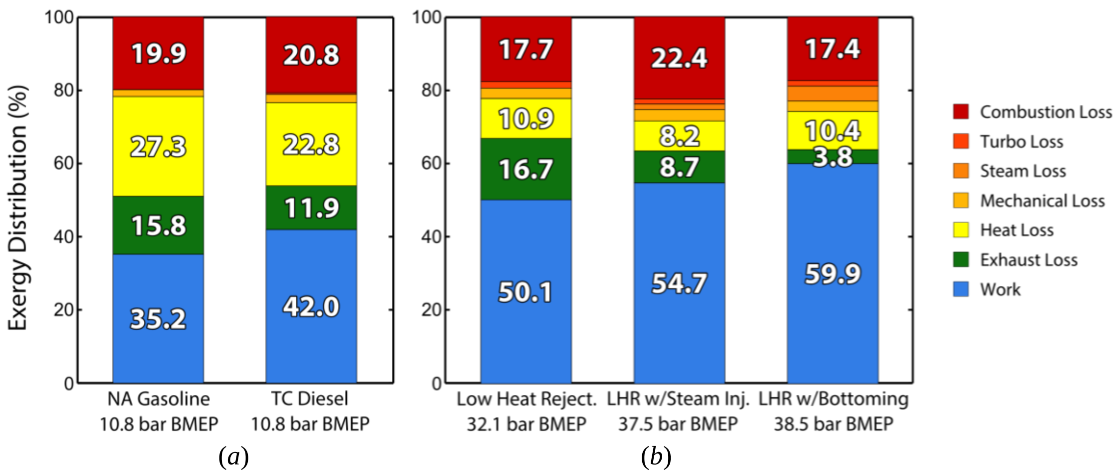

Figure 1: Exergy distribution comparison between *(a)* current state-of-the-art engines and (*b*) three advanced configurations [4].

As shown in Figure 1, the conventional gasoline and Diesel engines reach exergy efficiencies of only 35% and 42% respectively, while the advanced LHR engines are able to reach exergy efficiencies of up to 60%. These high efficiencies are only achievable by implementing aggressive measures such as thermal barrier coatings, asymmetrical expansion, turbocharging, and bottoming cycles to eliminate passive heat rejection (indicated by the yellow boxes) and recover exergy in the exhaust stream (indicated by the green boxes).

If we want to continue improving efficiency beyond 60%, what other strategies can we employ? Even by successfully implementing all of the aforementioned measures to recover exergy lost to heat transfer and exhaust, the efficiency of these advanced engines remains below 70%. From the exergy distributions in Figure 1b, we see that the losses are now so dispersed that the next logical place for improvement is the exergy loss due to combustion (indicated by the red boxes), which is at least 17%, even in the most advanced configuration.

In prior work for GCEP we have analyzed this loss of exergy due to combustion and shown that there are two ways it can be reduced: (1) by moving to states of high internal energy when conducting the combustion process—a concept we refer to as the *extreme states* principle—or (2) by avoiding the combustion process altogether by moving to a restrained chemical reaction instead [5, 6, 7]. Fuel cells are the only practical devices that implement restrained chemical reactions and are therefore candidate devices to incorporate into a system architecture that seeks to realize high efficiency.

Figure 2 shows an exergy analysis of a solid-oxide fuel cell operating at 1000°C and 1 atm on reformed methane. The small destruction bar indicates the primary advantage of fuel cells: They convert chemical energy to work while destroying very little exergy. On the other hand, the large exhaust and heat loss boxes indicate the primary limitation of fuel cells: They do not effectively extract thermal or mechanical exergy from a resource. Large exergy losses due to exhaust and heat transfer are preferable to large exergy destruction, however. As was seen in the case of evolving piston engines, these forms of exergy can be transferred to other devices and used elsewhere in the system via measures such as preheating reactant streams or adding a Rankine bottoming cycle.

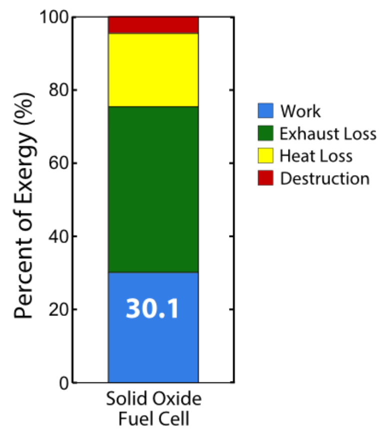

Figure 2: Exergy distribution of a solid-oxide fuel cell operating on reformed methane at 1000°C and 1 atm.

Managing these exergy transfers—work from the engine, work from the fuel cell, heat transfer and exhaust from each device—and the interplay between them, is the challenge of our research. Using exergy analysis to inform our decisions, we can carefully select operating points and strategically implement supporting thermodynamic devices to develop an engine architecture that realizes high efficiency at a scale suitable for distributed generation and transportation.

Internal Combustion Engines and Fuel Cells as Complementary Technologies

Our decision to combine IC engines and fuel cells in order to reduce exergy loss due to combustion is reinforced by the complementary nature of the two devices. Piston engines are inexpensive, can produce high efficiencies if properly configured, and are more efficient as load is increased. These characteristics provide a natural complement to fuel cells, which are costly and drop from approximately 70% LHV efficiency at lightly loaded conditions to less than 40% LHV efficiency at peak power. Additionally, the stringent fuel requirements for the fuel cell are offset by the IC engine's ability to combust a large range of fuels, which makes the overall system relatively fuel flexible. An engine can be used as a quick-start syngas generator (possibly coupled with a shift reactor) to provide hydrogen for a fuel cell. Finally, the two technologies can be closely integrated with supporting devices to allow for opportunities for thermal and chemical regeneration and provide the necessary balance of plant to efficiently run the overall system.

Background

The best real-world example we have seen of a mixed restrained/unrestrained engine architecture is a large-scale solid-oxide fuel cell/gas turbine/steam turbine (SOFC/GT/ST) triple cycle concept from Mitsubishi Heavy Industries (MHI) [8]. MHI has reported LHV efficiencies for this triple cycle in the range of 70-74% and SOFC element lifetimes of approximately 4,000 hours, which is in excess of current heavy-frame gas turbine maintenance intervals and adds credence to fuel cell reliability.

Our group has analyzed the MHI SOFC/GT/ST triple cycle to understand why it is capable of achieving such high efficiency [7]. The high efficiency was attributed to the complementary nature of the three types of work extraction: electrical in the SOFC, mechanical in the gas turbine, and thermal in the steam turbine. Each of these devices provides a near-independent method of extracting work, has low internal exergy destruction, and is well-matched to the form of exergy transferred to it by upstream components.

The question we ask here is whether we can achieve the efficiencies of the SOFC/GT/ST system at a smaller scale, one suitable for distributed generation or transportation. Moving to a smaller scale requires moving from a gas turbine engine to a piston engine. In addition to leveraging everything our lab has learned about piston engines, using an IC engine also enables the use of fuels that the SOFC/GT/ST system could not use without adding a fuel reformer and allows for start-up and power ramping capabilities that would be much more difficult with the MHI triple cycle.

Results

We have developed two system architectures to study the open-ended problem of how to best implement an IC engine/fuel cell combined cycle. These systems are being analyzed to refine system architectures and understand where experimental validation is needed as well as what unique advantages the IC engine/fuel cell combination enables. Based on our exploratory research—funded by an exploratory GCEP grant—we found two promising approaches that each have their own distinct benefits and will serve as a basis to guide future design iterations, which we refer to as the *low-temperature approach* and the *high-temperature approach*. Schematics for these two proposed systems are show in Figure 3.

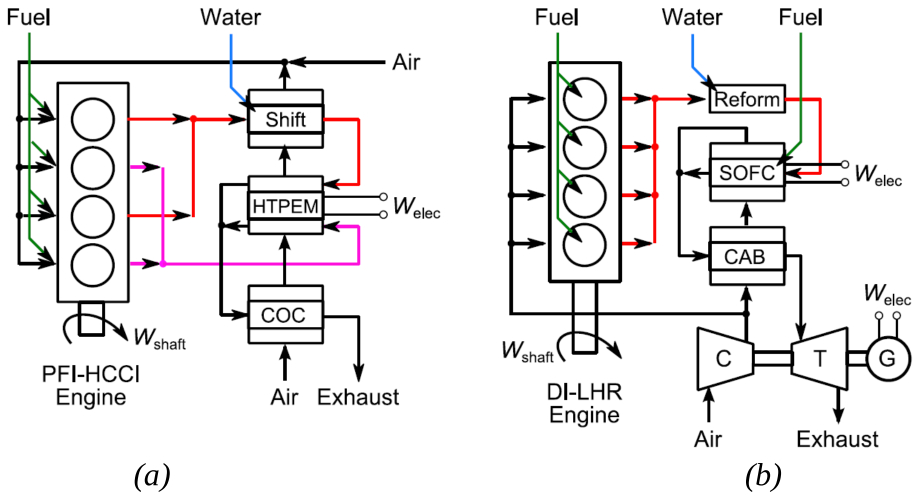

Figure 3: The two initial system configurations for mixed combustion/electrochemical engines. Shown in *(a)* is the *low-temperature approach* of a low-cost, fast start-up engine that uses a port fuel injection (PFI) and low-temperature combustion (via HCCI) in combination with a high-temperature PEM (HTPEM) fuel cell (~180°C). Shown in *(b)* is the *high-temperature approach* of a direct injection (DI), low heat rejection (LHR) engine in combination with a solid-oxide fuel cell (~800°C) and a turbocharger/generator.

The *low-temperature approach* builds from HCCI research and takes advantage of the lower temperature engine exhaust gases that match well with water-gas shift reactors and lower temperature fuel cells (such as HTPEM or phosphoric acid). This approach is expected to be capable of operating over a wide load range with good ramping capabilities while also providing high efficiency. The *high-temperature approach* builds on the previous high-temperature combustion research (such as low heat rejection direct-injection [6]) with high-energy exhaust gases. Gases at these temperatures are well matched to steam reforming and high-temperature fuel cells (such as solid oxide fuel cells). This approach is expected to be more efficient than the low-temperature approach but more difficult to adapt to a wide load range for transportation applications.

Modeling Results

Figure 4 shows the exergy breakdown of a system evolved from the *high-temperature approach* in Figure 3b. We evolve the architecture by using exergy analysis to locate the processes in the system that destroy exergy and consequently target these processes to reduce the system exergy destruction. For example, the SOFC is exothermic and must be cooled through heat transfer to maintain its temperature (approximately 1000°C). If this heat transfer cannot be utilized in other parts of the system—for example to make steam for the reformer—it must be rejected to the environment and that exergy is lost. In this case, we would change the system parameters to reduce this lost heat transfer as much as possible, evolving our system processes or parameters as needed. Figure 4 shows the results from a moderate amount of redesign and the introduction of a steam bottoming cycle to recover exhaust exergy, leading to a system with 63% exergy efficiency (65% LHV).

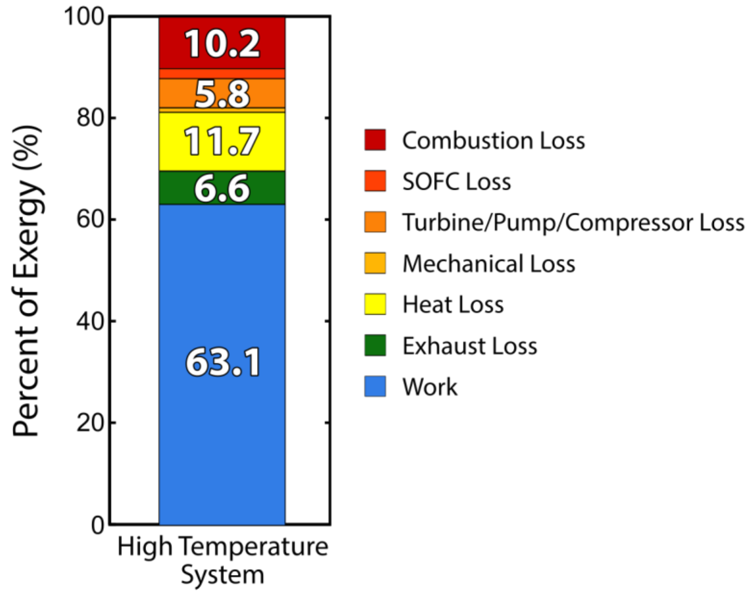

Figure 4: Exergy breakdown of the *high-temperature approach* system with an added steam bottoming cycle.

The yellow heat loss block seen in Figure 4 is noticeably large, and is due to the difficulty of carrying out a significant amount of heat transfer without large losses. Exergy destruction due to heat transfer is driven by the temperature difference between the two streams in a heat exchanger. Reducing the temperature difference is a difficult systems engineering problem and will be done on these systems once a candidate final system has been identified, with the expectation that some improvement can be made.

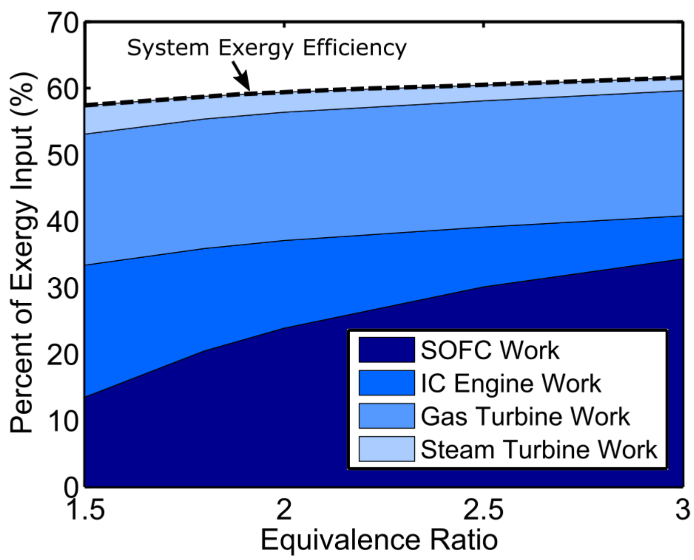

Figure 5: Exergy efficiency and work output by each device over a range of IC engine equivalence ratios for the *high-temperature approach* system with a steam bottoming cycle.

An interesting result from our modeling is the relationship between the amount of chemical energy conversion done in the IC engine and the overall system efficiency. Figure 5 shows the anticipated result that we achieve higher efficiencies as we shift more chemical energy conversion from the combustion process in the IC engine to an electrochemical process in a fuel cell. Also shown in Figure 5 is the percentage of work done by each work extraction device – the IC engine, fuel cell, gas turbine, and bottoming steam turbine. This relationship can be extrapolated to the extreme case where no chemical energy conversion takes place in the IC engine, which would now be comparable to the SOFC/GT/ST cycle that is being developed for grid-scale applications. So this result begs the question, *what is the engine's role in the system?*

While research is ongoing and it is difficult to draw conclusions at this point, we believe the engine plays four primary roles: (1) enabling the use of fuels that SOFC systems cannot internally reform (like alcohols or gasoline), (2) providing start-up power and ramping capabilities for a distributed- or transportation-scale system while the fuel cell is brought online, (3) reducing the size—and therefore cost—of the fuel cell while delivering the same power at nearly the same efficiency as the SOFC/GT/ST system and (4) increasing the power density of the system as compared to the triple-cycle while exceeding the efficiencies of the best IC engine-based systems.

Experimental Results

Our models use state-of-the-art performance metrics for existing devices and technologies (e.g., turbocharger efficiency, temperature limits of thermal-barrier coatings, etc.), and realistic-but-optimistic assumptions in areas where actual performance is unknown. In our research we are operating outside the bounds of conventional engineering devices, so we have developed a suite of experiments to provide validation for the assumptions we are using to model our systems. Unconventional processes we are using that are not well understood include IC engine rich combustion, fuel reforming in atypical conditions, and fuel cell operation using reformed engine exhaust gas as a fuel supply.

Two experimental engines have been used to perform rich-combustion experiments with gasoline, methanol, and ethanol. In addition to major gas emissions species, soot emissions were also characterized. Analytical chemistry methods are required to determine hydrocarbon speciation across the suite of experiments, so a gas chromatograph is being acquired that can provide speciation details of engine, reformer, water-gas shift, and fuel cell exhaust. This will provide more precise energy and exergy analysis of each component as well as a tool to calibrate the component and system models. Another benefit of hydrocarbon speciation is its ability to provide insight into specific species' roles in catalyst performance or degradation in either the chemical reactors (steam reformer/water-gas shift) or the fuel cell.

A steam reformer is being designed and built to determine what limitations exist on reforming exhaust gas as well as the ability to reform gasoline and alcohols to produce hydrogen-enriched gases for the fuel cell. While fuel reforming data are widely available, these data are not for the case of reforming in the presence of rich IC engine exhaust gases, so capability in that area is important and will also be used to calibrate the reformer model already in place.

Finally, a HTPEM cell has been designed and is being built to study the effects of reformed gas composition on the performance and lifetime. Studies have explored the presence of carbon monoxide on HTPEM performance, but the current system will potentially have other trace hydrocarbon species, and understanding their importance and learning how to incorporate those impacts in a model are a goal of this study.

Future Plans

The immediate work is in evolving the system model of the *high-temperature approach* to understand the trade-offs between the desirable capabilities introduced by having an IC engine and the efficiency gains due to shifting more chemical energy conversion to the fuel cell. Additionally, the thermal management in the system will be improved, increasing overall efficiency. Similarly, the system model of the *low-temperature approach* is being finished and will be analyzed and evolved in a similar fashion.

Experimentally, the gas chromatograph capabilities will be used to provide speciation data for the suite of experiments that will be done. The final design of the high-temperature reactor is being finalized and will be built this summer to enable the start of fuel and exhaust gas reforming experiments. These results will then be used to provide updated information to ensure the model is as accurate as possible.

Additionally, the HTPEM will be brought online and tested to provide modeling insight into the impact of carbon monoxide and other contaminants. Finally, reformed engine exhaust gas will be used in the HTPEM to provide proof of concept and to complete the engine-to-fuel cell demonstration.

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