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SAE REX: PHEVs and REEVs could open door for advanced combustion regime engines

7 November 2016

Increased market penetration of plug-in hybrid electric vehicles (PHEVs) and range-extended electric vehicles (REEVs) across vehicle segments could present an opportunity for emerging advanced combustion regime engines, such as those using various low-temperature combustion modes, according to a number of presentations at the SAE 2016 Range Extenders for Electric Vehicles Symposium held last week in Knoxville.

The REEV or PHEV also may present opportunities for more novel power sources such as turbines (Wrightspeed), fuel cell stacks (Nissan) or aluminum-air batteries (Phinergy and Arconic), speakers suggested. The REX symposium was sponsored by Mahle; the organizers were from Oak Ridge National Laboratory and Mahle.

In his introductory keynote, Michael Berube, Vehicle Technologies Office Director, Office of Energy Efficiency and Renewable Energy, noted the importance of both engine and fuel technology in a PHEV scenario.

> *If PHEVs are going to play a big role, what is the fuel source for that? How efficient will it be? You're going to need to have very scalable low-carbon fuels if you are going to have PHEVs be a path for deep decarbonization. We certainly believe at DOE that that is a possible path. We don't have one solution that we are here to say is the right one, but we believe that PHEVs could potentially be a key pathway. But to do that, we need to think about the engine.*

> *High efficiency engines with low-carbon fuels clearly is a major, major pathway. Not the only one. But we believe this a major pathway.*
>
> —Michael Berube

Berube went on to reference the importance of DOE's major new Co-Optima initiative (earlier post), an effort to co-optimize new fuels and light-, medium- and heavy-duty engines which together could achieve very significant performance improvements. Specifically, Co-Optima is targeting a reduction in per-vehicle petroleum consumption by 30% vs. the 2030 base case, which is constrained to using today's fuels.

In its short life-time, Co-Optima has grown to a 9-laboratory team with more than 130 researchers tackling different aspects of the problem.

> *We believe that [Co-Optima] is a major, major aspect of how we can achieve these [decarbonization] numbers. We believe that, using both of those together, co-optimizing the fuel and the engine, and combining it now with the overall electrified vehicle, you can get dramatic reductions in the overal CO_2 level.*
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> *The focus is what fuel properties maximize engine perfromance. What if that ICE is now operating in a very narrow range, powering the electric vehicle?*
>
> *What I suggest for you, as you think about PHEVs, think about now having very optimized engines, very optimized fuels that have a high level of renewables in those fuels. You now have a low-carbon fuel that can be operated in engines that are operating in a much more narrow band. Within that band, we can get to a very high level of efficiency. There is a very strong case to be made for that PHEV world.*
>
> —Michael Berube

In a subsequent talk, Scott Curran from ORNL—one of the organizers of the symposium along with Robert Wagner from ORNL and Hugh Blaxill from Mahle Powertrain—noted that the ability to decouple the engine from the drive cycle, as well as the availability of high voltage current, can help overcome challenges facing advanced engine and emission control systems developers.

> *The role of the internal combustion engine is changing. We still see a prominent role for these engines moving forward. The ability to refuel large amounts of energy very quickly is going to remain extremely attractive to consumers.*
>
> *The EPA Tier 3 emissions standards are going to be incredibly difficult to meet. We are going to keep relying on advanced engine*

> *technologies to meet these regulations, and as we start looking for higher and higher degrees of electrification, these hybrid systems are going to have to integrate all the opportunities and challenges for the engine, the aftertreatment and the power electronics all to work as one. That's where things start to get really exciting.*
>
> *As we look along the spectrum of increasingly electrified vehicles, what is the design space that this increasing amount of electrification opens up to optimizing? As we start to explore this higher degree of electrification, there are going to be some very different design requirements for internal combustion engines.*
>
> —Scott Curran

One example of the potential for low-temperature combustion (LTC) engine technology for range extended electric vehicles (REEV) presented at the Symposium was work by Ali Solouk and Assistant Professor Mahdi Shahbakhti at Michigan Technological University.

The category of LTC spans a range of specific technologies; these are of great interest as they promise to improve fuel economy, and reduce NO_x and soot emissions by improving the in-cylinder combustion process.

LTC technology faces two main difficulties: first, a narrow operating range, which limits the use of the technology in conventional powertrains; second, complex combustion control, particularly durient transient operations. However, when applied in a range-extending application (i.e., as a generator), an LTC engine can work in a narrow operating area and increases the range of the battery pack.

Souk and Shahbakhti modified a turbocharged 2-liter GM Ecotec direct injection engine to function as a multi-mode LTC/Spark Ignition engine. The LTC modes included homogenous charge compression ignition (HCCI) and reactivity controlled compression ignition (RCCI) LTC engine.

Major changes to the base engine included:

- design and programming of a new Engine Control Unit (ECU)
- the addition of a port fuel injection system
- the capability to adjust intake temperature, pressure, and dilution level through the use of an intake air heater, supercharger, and Exhaust Gas Recirculation (EGR) rate modulation, respectively.

The engine functions as a generator for the battery pack.

Optimization results showed that in the UDDS driving cycle, the single-mode HCCI and RCCI engines offer 12% and 9% fuel economy improvement, respectively over a single-mode SI engine in the REEV. These improvements increase to 13.1% and 10.3% in the HWFET driving cycle. This fuel economy improvement is reduced to 3% in comparison to a modern CI (i.e. diesel) engine in the HWFET driving cycle.

Simulation results showed that the LTC engine offers higher fuel economy improvement in more aggressive driving cycles (e.g., US06) compared to less aggressive driving cycles (e.g., UDDS).

The optimal control algorithm enhanced the fuel economy by 17.0% over the rule-based strategy in a hybrid electric vehicle integrated with an LTC engine.

Using a “multi-mode”—i.e., both HCCI and RCCI—instead of “single-mode” LTC engine in the REEV provided 2% more fuel economy improvement, depending on the type of the driving cycle. Reducing the mode-switching fuel penalty increased the fuel economy improvement beyond 2%.

Among the LTC modes, HCCI was the dominant engine operating mode. If the fuel penalty to the RCCI mode decreased by 95%, the engine operated near to 45% of its ON time in the RCCI mode.

The study also found that HCCI and RCCI were more favorable from the NVH considerations, compared to the SI engine. This is due to use of low engine speeds in the LTC modes.

The team will be presenting a new paper on their work at the SAE 2017 World Congress next year.

Resources

- Ali Solouk, Mohammad Shakiba-herfeh, Kaushik Kannan, Hamit Solmaz, Paul Dice, Mehran Bidarvatan, Naga Nithin Teja Kondipati, Mahdi Shahbakhti (2016) “Fuel Economy Benefits of Integrating a Multi-Mode Low Temperature Combustion (LTC) Engine in a Series Extended Range Electric Powertrain” SAE 2016-01-2361

November 7, 2016 in Co-Optima, Electric (Battery), Engines, Fuel Efficiency, Fuels, Hybrids, Low Temperature Combustion, Plug-ins | Permalink | Comments (8)

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