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# Flameless Combustion Engines in the Transition to Hydrogen

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**Abstract**

Advanced internal combustion engines (ICE), fueled by hydrogen and other non-petroleum fuels, represent the nation's greatest mid-term opportunity for reducing petroleum dependence. This project is to research and demonstrate new paths to stretch the efficiency of ICEs toward 60%, and provide a foundation for multi-year DOE programs in the area. Contrary to widespread opinion, combustion engines have approximately the same theoretical potential efficiency as fuel cells. Of the mechanisms that presently hold combustion engines to about 45% peak efficiency, the thermodynamic losses in combustion via high-temperature, propagating flames are prominent. Exploring "flameless" combustion for maximum efficiency will be our focus. Considered thus far for their emissions benefits, new, low-temperature combustion modes have not been studied nor exploited for efficiency benefits to a significant extent.

**Body of Progress Report**

Advanced ICEs are central to the nation's opportunity for mid-term petroleum savings while fuel cells and hydrogen supply develop. To maximize the benefits, combustion engine efficiency must move beyond present levels. In spite of common misconceptions, there is no fundamental barrier to ICEs reaching 60% efficiency. Our objective here is to define engineering paths to actually achieve this efficiency for both transportation and distributed power generation.

Our research focus is on reducing combustion exergy losses by application of flameless combustion methods. These losses result from the entropy produced by unrestrained chemical reactions; e.g., reactions far from chemical equilibrium in the flame front that dissipate 20-25% of the fuel energy as exhaust heat instead of work. This is one of the largest losses and remaining barriers to substantially higher engine efficiency. Theoretical calculations indicate that if ICE combustion reactions could be slowed and spatially distributed, fuel efficiencies would be enhanced. Our technical approach has focused on three paths:

- Exploitation of recently discovered volumetric combustion modes in piston engines;
- Optimization of time scales of work extraction and combustion reactions; and
- Utilization of 'chemical looping' (oxygen storage to stage the combustion reactions).

A collaborative team of combustion and thermodynamics experts was formed to help coordinate the research. This team consists of ORNL staff and prominent engine researchers from key universities, industry, and Sandia National Laboratory. In December 2004, the team met at ORNL and concurred with our objectives and approach.

To support theoretical calculations and analysis of experimental data, we constructed a set of computer codes for evaluating thermodynamic properties and equilibrium states of gas and gas-solid combustion systems of interest. Although there are commercial combustion codes for similar calculations in certain contexts, none were sufficiently flexible for the desired 2nd Law of Thermodynamics analyses of arbitrary combustion trajectories. These tools are now available for any type of combustion exergy modeling, including parallel models and models of previously unknown types of combustion. A lowdimensional multi-zone ICE model for simulating the reaction and heat transfer processes in non-standard combustion modes was developed. This code extends our capability to analyze experimental data and study novel combustion modes and control strategies. The code is also tailored to interface with commercial engine software that address auxiliary systems such as fuel injection and air handling. A license for Ricardo WAVE software was obtained to provide the latter.

The new analytical tools were initially used study of the effects of combustion preheat and exhaust gas recirculation on exergy losses, resulting in a concept for a physically realistic isobaric combustor and gas turbine system with approximately 70% efficiency. Chemical looping combustion (CLC), a relatively new concept for staging combustion, was identified to have theoretical efficiency and emission advantages, but numerous technical hurdles. A conceptual embodiment for a CLC engine was developed and a patent disclosure is in preparation.

Collaborations were established with the University of Wisconsin and Texas A&M University to evaluate global exergy distribution in piston-cylinder engines. Our collaborators are utilizing their own models that have been extensively tested and published. The collaboration provides the opportunity to validate our in-house piston-cylinder code and enables a greater variety of approaches to be studied.