IN-CYLINDER PROCESSES OF NATURAL GAS COMBUSTION MODES

Mark Musculus • Sandia National Laboratories • (925) 294-3435 • mpmuscu@sandia.gov
Dawn Manley • Sandia National Laboratories
Brad Zigler • National Renewable Energy Laboratory

OVERVIEW

This presentation describes planned activities in natural gas (NG) combustion research at the Combustion Research Facility (CRF) of Sandia National Laboratories (SNL). The presentation is comprised of three parts. First, the perspective of the United States (US) NG market and the US Department of Energy (DOE) on and research and development (R&D) needs are reviewed, closing with emphasis on vehicle end-use R&D needs for in-cylinder combustion. Second, four NG in-cylinder combustion strategies currently deployed in production engines are briefly described. Some highlights of progress to date on developing understanding of in-cylinder processes using optical engines and other facilities is reviewed for each of the four NG combustion strategies. Comments on knowledge gaps yet to be filled and are also offered. The presentation closes with plans to modify the existing heavy-duty (HD) optical engine at SNL's CRF for multiple NG fueling and ignition concepts to enable operation with all four NG combustion strategies currently deployed, as well as other advanced concepts or variations on the current strategies.

US PERSPECTIVES ON NG

For the US, the most recent energy production and usage data available (2013) show that NG production (26.6 quads) is comparable to total energy usage for transportation (27.0 quads), but only 3% of NG production is currently used for transportation. This demonstrates potential for significant impact on transportation energy usage by NG. The US climate action plan promotes greater NG usage to offset greenhouse gas (GHG) emissions, including for transportation. Although the worldwide NG vehicle fleet, largely passenger cars, has grown 20% annually for the past decade reaching 17 million vehicles in 2012, growth in the US passenger car market has been much smaller. In the next few decades, little growth is projected in the US NG passenger car market, but 10% annual growth is projected for the US NG HD market. This growth is anticipated in part due to the large cost differential for NG relative to diesel and gasoline fuels. Fuel costs are more important for HD vehicle applications, and the cost differential is expected to persist for many decades. Hence, greater penetration of NG vehicles in the HD market will be driven by both an economic pull and a policy push for GHG reduction. To achieve greater NG penetration in the US HD market, improvements are needed in many steps in the NG supply chain. Planned work at SNL's CRF focuses on vehicle end-use, in particular, NG in-cylinder combustion issues.

NG COMBUSTION STRATEGIES IN CURRENT PRODUCTION ENGINES

Four different NG engine combustion strategies are currently deployed in production engines:

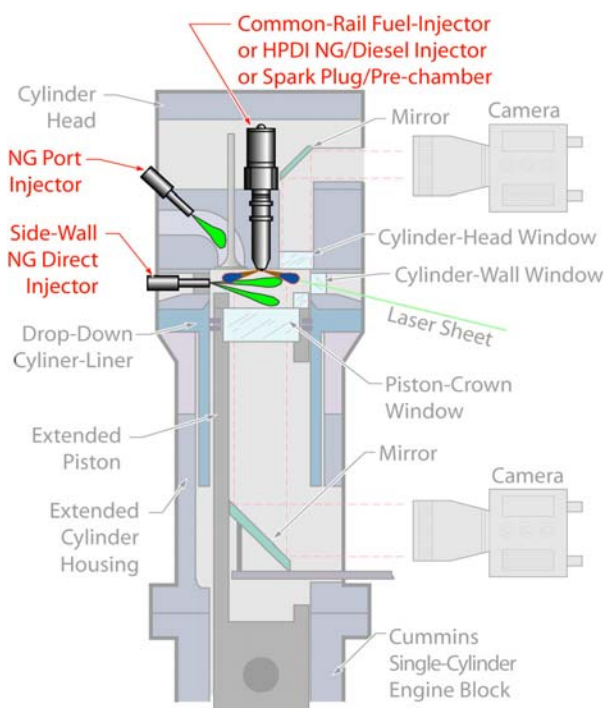
- <u>Stoichiometric Premixed Spark-Ignition (SPSI)</u> engines use NG premixed with the intake gases to stoichiometric proportions and ignited by a spark. Typically, cooled exhaust-gas recirculation (EGR) reduces in-cylinder temperatures and thereby also reduces formation of nitrogen oxides (NOx), and eases the heat load on the engine. With stoichiometric mixtures,

simultaneous exhaust aftertreatment of NOx, carbon monoxide (CO) and unburned hydrocarbons (UHC) can be achieved by a three-way catalyst. NG injection is typically in the intake port, though early direct injection is also conceivable to create mixture heterogeneity.

- Lean-Premixed Spark-Ignition (LPSI) engines use NG premixed with air and/or EGR to overall fuel-lean proportions and ignited by a spark plug or pre-chamber. Much like homogeneous charge compression ignition (HCCI) or partially premixed compression ignition (PPCI), operation with uniformly fuel-lean mixtures reduces combustion temperatures and NOx formation so little or no exhaust NOx aftertreatment is required. Oxidation catalysts are still required for carbon monoxide (CO) and methane slip. NG port injection is typical, though early direct injection is also conceivable.
- Lean-Premixed Diesel-Pilot (LPDP) engines are similar to LPSI, but ignition is achieved by a small pilot injection of diesel fuel rather than by a spark plug or pre-chamber. The high cetane number of the diesel fuel enables chemical autoignition, and the broader mixing of the diesel fuel jets into the combustion chamber provides a more robust and larger ignition kernel than for spark ignition engines, resulting in generally more robust ignition. After ignition, combustion can proceed through the fuel-lean NG mixture by flame propagation or sequential autoignition, or a combination of both, depending on the local conditions.
- Direct-Injection Diesel-Pilot (DIDP) engines use NG injected directly into the cylinder charge of air and EGR. The diesel pilot ignition can occur before, during, or after the NG injection. NG premixing can be increased by delaying the diesel pilot injection. Combustion after ignition is generally mixing-limited, similar to conventional diesel engines. As a result, the combustion and emissions for DIDP NG engines can be similar to conventional diesel engines, with NOx forming in the hot diffusion flame and soot forming within rich mixtures in the jet interior.

MODIFICATION OF EXISTION SNL HD DIESEL OPTICAL ENGINE FOR NG

The existing SNL HD diesel optical engine will be modified for various NG fueling strategies to provide a common-platform NG optical engine for developing the missing science base needed to optimize NG combustion. Establishing this science base will enable engineering developments to overcome technical barriers and accelerate the deployment of NG-fueled engines to reduce GHG emissions. The model for this type of work is decades of optical engine research for compression ignition (diesel) engines, which yielded understanding embodied in a world-renowned diesel "conceptual model" that has proven essential for diesel engine development. Stakeholders in



Heavy-duty optical diesel engine with proposed modifications for natural gas fueling and ignition.

industry concur that a NG conceptual-level understanding would greatly aid development/deployment of NG engines.