Section VII. Conversion Devices

VII.A Conversion Devices - Turbines

VII.A.1 Reduced Turbine Emissions using Hydrogen-Enriched Fuels

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Objectives

- Quantify effect of hydrogen addition on flame stability, combustor acoustics, emissions and efficiency in a gas turbine.
- Establish a scientific and technological database for lean combustion of hydrogen-enriched fuels.
- Establish numerical simulation capabilities that will facilitate design optimization of hydrogen and hydrogen-enriched lean gas turbine combustors.
- Develop criteria for use of hydrogen addition as a control knob to eliminate instabilities related to varying product gas composition.

Approach

- Design and fabricate a lean premixed swirl burner that simulates the basic features of gas turbine combustors.
- Apply advanced experimental diagnostics to understand fluid dynamics, combustion chemistry, and pollutant formation.
- Develop a computational model for combustor performance in parallel with an experimental project based on next generation Large Eddy Simulation (LES) technique. Use experimental database for model validation.
- Identify problem areas in practical gas turbine combustors where hydrogen enrichment of hydrocarbon fuels could be beneficial.

Accomplishments

- Completed design and fabrication of lean premixed swirl burner that will be used to study combustion of H_2-blended hydrocarbon fuels in stationary gas turbine environment. (Collaboration with the National Energy Technology Laboratory).
- Completed design and fabrication of prototype H_2/air burner for aircraft gas turbine applications. Characterized relationship between flame and fluid dynamics and evaluated fuel/air mixing. (Collaboration with NASA Glenn.)
- Formed collaboration with General Electric Aircraft Engines (GEAE) to evaluate production fuel injector for use with hydrogen-blended fuels.
- Developed international effort through the International Energy Agency (IEA) to address aspects of H_2-enriched hydrocarbon fuels for low emission, high efficiency gas turbine combustion.

Future Directions

- Assess and verify the flow, flame characteristics and dynamic stability limits of the lean premixed hydrogen swirl burner.
- Establish a representation of the turbulent recirculating flow characteristics in the swirl burner using the LES model approach.
- Establish a framework for modeling hydrogen-enriched lean premixed combustion in the presence of acoustically active flame processes.
- Complete development of test matrix for GEAE swirlcup fuel injector and perform testing. Identify areas where hydrogen enrichment could be beneficial.
- Continue the formation of a broad consortium of industrial partners.
- Continue development of international collaborations, both directly and through the IEA.

Introduction

The development of advanced combustion capabilities for gaseous hydrogen and hydrogen-blended hydrocarbon fuels in gas turbine applications is currently an area of much interest. Driving this interest are several needs. One need is the cost-effective utilization of alternative fuels with a wide range of heating values. For example, fuels containing significant hydrogen are often produced as a by-product in Coal-Gasification Combined Cycle installations. These product gases could provide a significant source of cost-effective fuels for gas turbines. A second need is related to the recognition that ultra-lean premixed combustion is an effective approach to NO_x emissions reduction from gas turbine engines. Hydrogen blended with traditional hydrocarbon fuels significantly improves flame stability during lean combustion and allows stable combustion at the low temperatures needed to minimize NO_x production.

A longer-term need is to eliminate unburned hydrocarbon (UHC) and CO_2 emissions. Gas turbines account for 20% of U.S. CO_2 emissions, which is a significant fraction of the total current CO_2 emissions. This number will increase as natural gas turbines replace older coal-fired steam generation plants. The use of hydrogen-blended hydrocarbon fuels thus provides both a solution to the immediate need for NO_x reduction, and also provides a transition strategy to a carbon free energy system in the future.

Approach

The addition of hydrogen to hydrocarbon fuels affects both the chemical and physical processes occurring in flames. These changes affect flame stability, combustor acoustics, pollutant emissions, and combustor efficiency. Few of these issues are clearly understood. This project will investigate issues surrounding hydrogen and hydrogen-enriched hydrocarbon fuel use and will include studies of chemical kinetics, fluid dynamics and flame structure to better define and understand these issues. Both experimental and modeling approaches are being utilized. The experimental data will be obtained using an array of advanced laser diagnostic techniques that provide information on flame structure, fluid dynamics, combustion gas species concentrations and temperature. These measurements, in addition to providing direct insights into the effects of hydrogen enrichment on combustion and pollutant emissions, will provide the technological database needed for the parallel development of a numerical code, based on the LES technique, to simulate lean premixed combustion of hydrogen and hydrogen-enriched fuels. Close collaborations have been developed with industrial partners to provide a mechanism for the transfer of this technology to practical applications in stationary and aircraft gas turbines. These collaborations will facilitate the identification of problematic areas related to practical gas turbine design and hardware. Areas where hydrogen addition could prove beneficial will be identified, and the potential merits of hydrogen-enriched hydrocarbon fuels will be demonstrated.

Results

The design and fabrication of a lean premixed swirl burner representative of land-based industrial applications was completed. This burner will be used to study combustion of hydrogen and hydrogen-blended hydrocarbon fuels. The design emphasizes well-characterized flow and boundary conditions to facilitate the development of a database for LES model validation. Emphasis with regard to LES has been placed on providing support calculations for design purposes and establishing an initial baseline-modeling framework for treatment of hydrogen-enriched, premixed methane flames. This burner is shown in Figure 1. The burner design is operationally relevant to industrial devices and is optimally tuned for flow and diagnostic capabilities at the Sandia Combustion Research Facility.

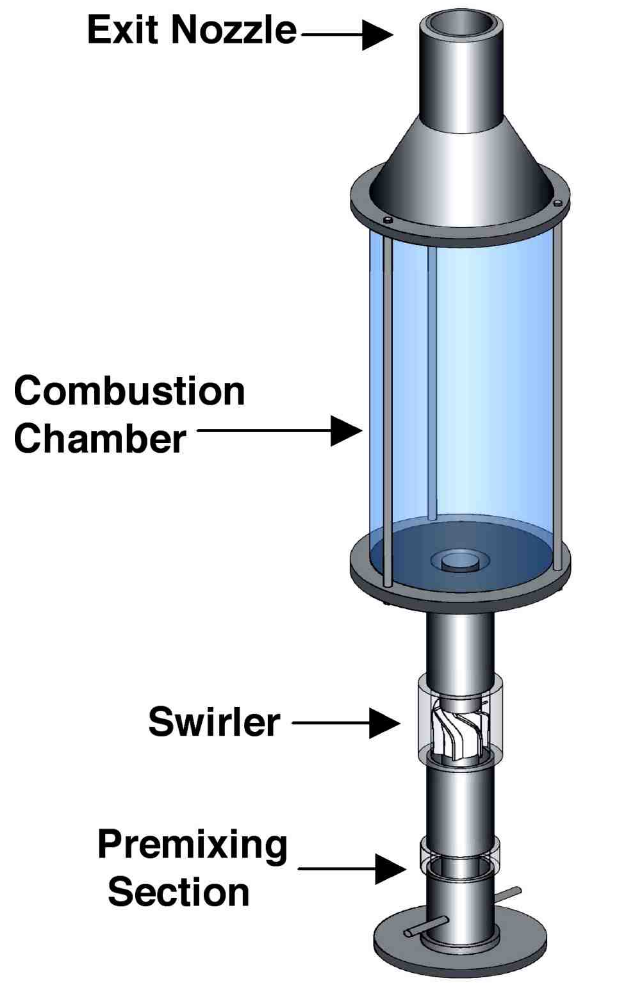

Figure 1. Lean premixed swirl burner designed to study combustion of hydrogen and hydrogen-blended hydrocarbon fuels.

The design and fabrication of a prototype hydrogen/air burner for aircraft gas turbine applications was completed in collaboration with NASA Glenn. The stability and burning characteristics of fuel-lean hydrogen/methane/air flames were characterized over a range of operating conditions. Figure 2 shows the effect of hydrogen addition on flame stability, where the variable n_{H2} is the fraction of hydrogen in the fuel (n_{H2}=0 corresponds to pure methane and n_{H2}=1 is pure hydrogen). The equivalence ratio is a measure of the fuel/air ratio. These measurements were obtained by igniting the flame and then decreasing the fuel/air ratio until the flame is completely extinguished, or is blown out. The flame typically becomes unstable as the blowout condition is approached. Increasing the hydrogen content from 70% to 100% results in a significant shift in flame blowout conditions to leaner fuel/air ratios. Since operation at leaner fuel/air ratios results in a lower flame temperature and reduced NO_x emissions, it is clear that hydrogen addition allows stable operation at the lean operating conditions needed to limit NO_x emissions. Mixing of the fuel and air is also important, since incomplete mixing leads to higher flame temperatures, increased NO_x and lower efficiency. Planar Laser Induced Fluorescence (PLIF) measurements of acetone, which was added as a fuel tracer, were obtained to evaluate the mixing of the fuel and air. Based on these measurements, design improvements will be identified and implemented. PLIF measurements of the hydroxyl (OH) radical, which is important to flame chemistry, were obtained to characterize the relationship between the flame and fluid dynamics.

The use of hydrogen addition to natural gas feedstocks of midsize (30-150 megawatt) gas turbines was analyzed as a method of reducing NO_x. Cost comparisons were made with current control technologies for both existing and new systems to determine its benefits and market feasibility. Less than 3 ppm NO_x should be achievable with 15% H_2 addition. The comparisons in Figure 3 show that 15% H_2 addition is cost competitive with both conventional Selective Catalytic Reduction (SCR) and high temperature SCR over a wide range of plant

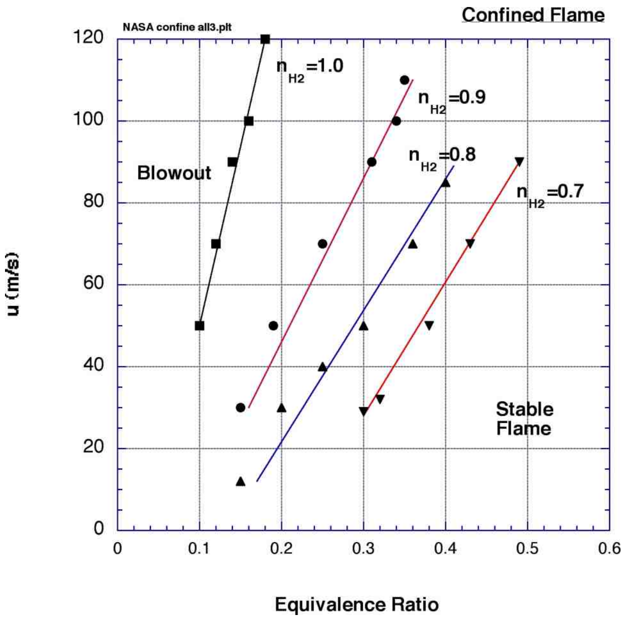

Figure 2. Effect of Hydrogen Addition on Flame Stability in Prototype Hydrogen/Air Burner

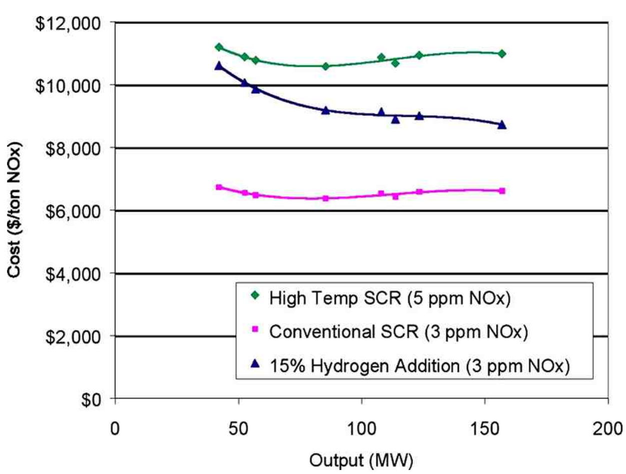

Figure 3. Cost Comparison of 15% Hydrogen Addition with Current NO_x Control Technologies

power outputs. Higher levels of hydrogen addition, while somewhat more expensive, should offer even lower NO_x emissions.

Conclusions

- Hydrogen addition significantly improves flame stability and allows stable burner operation at the lean fuel/air ratios needed for reduced NO_x emissions.
- Hydrogen addition for NO_x reduction to the 3 ppm level is cost competitive with current control technologies and has the potential to reduce NO_x emissions lower than any other control strategy.

Publications

1. R. W. Schefer, D. M. Wicksall and A. K. Agrawal: "Combustion of Hydrogen-Enriched Methane in a Lean Premixed Swirl-Stabilized Burner", Proceedings of the 29th Symposium (International) on Combustion, (2002).
2. R. W. Schefer: "Hydrogen Enrichment for Improved Lean Flame Stability", International Journal of Hydrogen Energy (accepted) 2002.
3. R. W. Schefer: "Reduced Turbine Emissions using Hydrogen-Enriched Fuels", Proceedings of the U.S. DOE Hydrogen Program Review, May 6-8, Boulder CO (2002).

Presentations

1. R.W. Schefer: "Reduced Turbine Emissions using Hydrogen-Enriched Fuel", 14th World Energy Conference, Montreal, Quebec, Canada, June 9-13, 2002.
2. C. Termaath, E. Skolnick, J. O. Keller and R. W. Schefer: "Emissions Reduction Benefits from H_2 addition to Midsize Gas Turbine Feedstocks", 14th World Energy Conference, Montreal, Quebec, Canada, June 9-13, 2002.

VII.B Internal Combustion Engines

VII.B.1 Internal Combustion Engines Research And Development

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Objectives

- Design and demonstrate high efficiency, low emissions hydrogen fueled 30 kW electrical generator
  - 50% fuel to electricity conversion efficiency and near-zero emissions

Approach

- Utilize highly developed piston engine technology
- Combine free-piston, linear alternator and homogeneous charge compression ignition to achieve the following:
  - Ideal Otto cycle performance
  - Electronic compression ratio control
  - NO_x control by low equivalence ratio

Accomplishments

- Developed full-scale linear alternator test capability
- Designed two-stroke cycle scavenging system
- Completed analysis of power density and performance for aircraft applications (NASA funded)
- Evaluated 2 kW size combustion experiment (Sandia LDRD funded)

Future Directions

- Complete scavenging system experiment fabrication and testing
- Develop comprehensive system model
- Quantify linear alternator performance
- Form industrial consortium for commercial application

Introduction

Electrical generators capable of high conversion efficiencies and extremely low exhaust emissions will no doubt power advanced hybrid vehicles and stationary power systems. Fuel cells are generally considered to be ideal devices for these applications where hydrogen or methane is used as fuel. However, the extensive development of the internal combustion engine and the existence of repair and maintenance industries associated with piston engines provide strong incentives to remain with this technology until fuel cells are proven reliable and cost competitive. In addition, the fuel cell may not

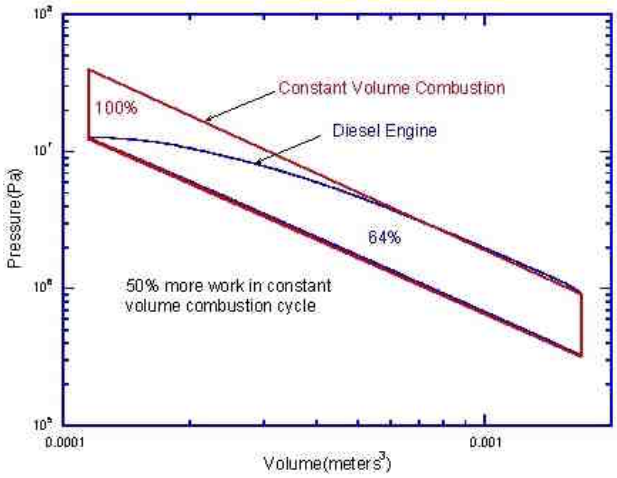

Figure 1. Modern 4-Stroke Heavy Duty Diesel Engine

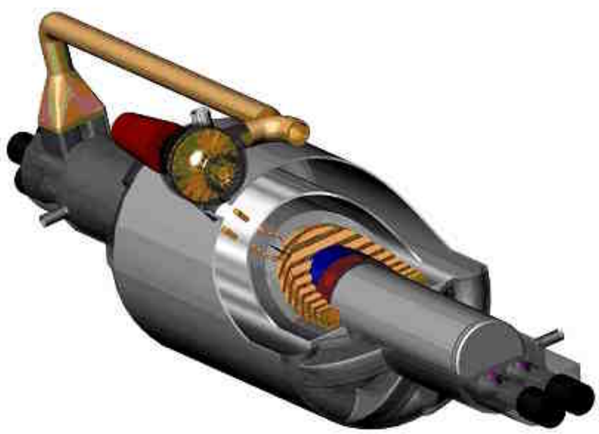

Figure 2. Free-Piston Linear Alternator

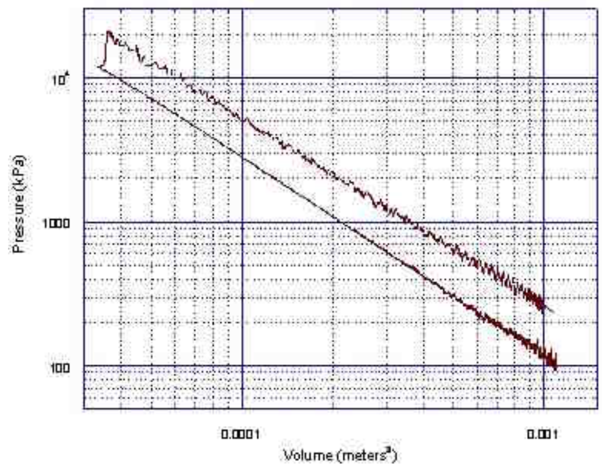

Figure 3. Hydrogen HCCI Combustion using the RCEM

offer significant efficiency advantages relative to an optimized combustion system.

In Figure 1, the amount of work attained from a modern 4-stroke heavy-duty diesel engine is shown. The results indicate that under ideal Otto cycle conditions (constant volume combustion), 56% more work is available than from an ideal constant pressure combustion (ideal diesel) cycle. This extreme case of non-ideal Otto cycle behavior serves to emphasize how much can be gained by approaching constant volume combustion systems.

Approach

The free-piston linear alternator illustrated in Figure 2 has been designed in hopes of approaching ideal Otto cycle performance through homogeneous charge compression ignition (HCCI) operation. In this configuration, high compression ratios can be used and rapid combustion can be achieved.

The linear alternator is designed such that electricity is generated directly from the piston's oscillating motion. Combustion occurs alternately at each end of the piston, and a modern two-stroke cycle scavenging process is used. The alternator component controls the piston's motion and, thus, the extent of cylinder gas compression. Compression of the fuel/air mixture is achieved inertially, and as a result, a mechanically simple, variable compression ratio design is possible with sophisticated electronic control.

The combination of the HCCI combustion process and the free-piston geometry is expected to result in significant improvements in the engine's thermal efficiency and its exhaust emissions.

Combustion System - Tests

Figure 3 shows the result of one of the HCCI combustion analyses. In this investigation, a single-stroke rapid compression-expansion machine (RCEM) was used to compression ignite homogeneous fuel/air mixtures. The piston, for all practical purposes, does not move during the combustion event. In the free-piston configuration, high pressure-rise rates can be handled without difficulty since there are no load-bearing linkages, as in crankshaft-driven engines.

Figure 4. Alternator Tester

Results - Linear Alternator

Two parallel paths are being pursued to develop the linear alternator. First, an alternator is being designed, built and tested in-house. In parallel, Magnequench, Inc. has designed and fabricated an alternator for this application. Both alternators will be tested under full design output conditions. A picture of the alternator tester is presented in Figure 4.

Two Stroke-Cycle Scavenging System

Our approach is to utilize multi-dimensional modeling (KIVA–3V) to design the scavenging system and then to validate the computational predictions for selected operating conditions with the use of a single-cycle scavenging experiment.

Important goals to be achieved with the scavenging design are high scavenging efficiency (η_{sc}>90%) and high trapping efficiency (η_{tr}>97%).

For the computational study, inverted-loop and uniflow scavenging methods were investigated. A loop-scavenged option was investigated first due to its potential for a mechanically simple system.

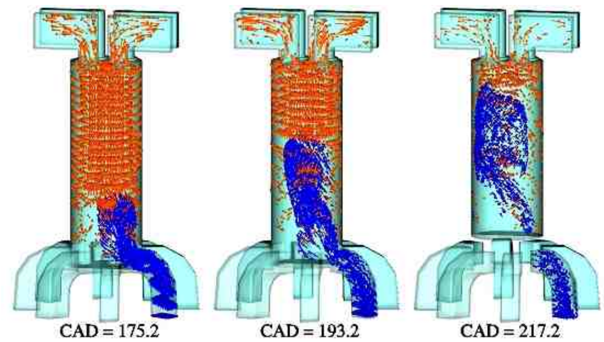

Figure 5. KIVA-3V Calculated Uniflow Scavenging

However, the mixing dynamics encourages fuel short-circuiting through the exhaust port. Additionally, for the configurations considered either high pumping losses or low power output must be accepted in order to achieve adequate cylinder charging.

An inverted-loop option was investigated next, with the intent of improving the trapping characteristics by placing the inlet ports above the exhaust ports. However, KIVA results showed the cylinder cannot be adequately charged, and a low scavenging efficiency (η_{sc}~0.45) and highly stratified charge result at the time of combustion.

The final scavenging option studied was a uniflow arrangement. In this configuration, four exhaust valves are located in the cylinder head, with intake ports located circumferentially around the bottom of the cylinder. Variation of the inlet port geometry and exhaust valve timing resulted in a more acceptable 83% scavenging efficiency with less than 1% short-circuiting of the inlet flow. Further, a low driving pressure can be used to adequately recharge the cylinder. An example of the in-cylinder flows for this arrangement is shown in Figure 5.

NASA Study

NASA-Langley requested assistance from Sandia to determine the feasibility of free-piston electrical generators in providing propulsive power for aircraft. The concept is to distribute generators throughout the aircraft and utilize electric motor powered fans to propel the aircraft.

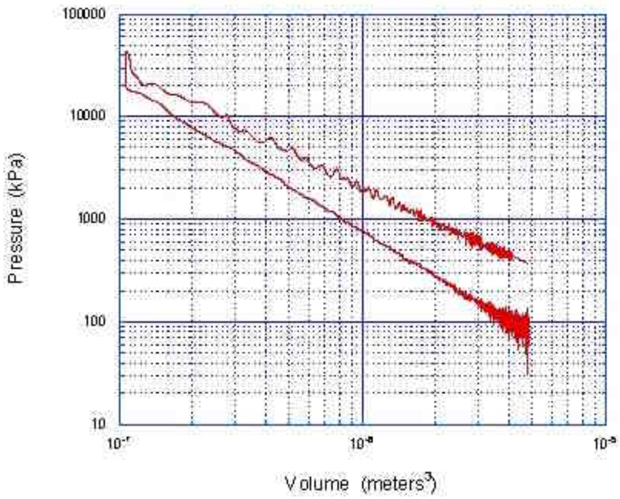

Figure 6. HCCI Combustion using the Small RCEM

One discovery made during this study was that while turbocharging the engine does not allow significantly increased power output per stroke due to peak pressure limitations, it does appear to be capable of providing all of the pumping work necessary to scavenge the combustion chamber. The result of this is that we will incorporate a turbocharger into the baseline 30 kW prototype design.

Another interesting discovery was that increased boost pressures with hotter fuel/air mixtures can maintain peak pressures similar to unboosted operation, but this results in significantly increased oscillation rates, which in turn increase the power output of the device.

Reduced-Size HCCI Combustion System

Another area for which the Advanced Generator Program has additional support is the investigation of a greatly reduced power output device. Funding is through internal laboratory sources with the objective of determining if the free-piston approach would work well for a single-occupancy vehicle that requires only 2 kW of output power. A small, rapid compression-expansion machine was fabricated with a bore of 1.2 cm, compared to the larger RCEM dimension of 7.6 cm. Figure 6 shows the near Otto cycle performance achieved, which is similar to that shown in Figure 3. Efficiencies were comparable to the 30 kW experiment.

Conclusions

A novel combustion-driven reciprocating electrical generator has been designed to produce 50% fuel to electricity conversion efficiency and essentially zero emissions. The prototype design is moving forward, with quantification of the performance of each piece of the prototype proceeding. To date no unsolvable technical barriers have materialized.

VII.B.2 HCNG Heavy Duty Vehicle Prime Mover

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Objectives

- Develop a low-emissions heavy-duty vehicle engine package to seamlessly repower today's buses and trucks with existing natural gas and diesel engines.
- Exceed DOE's goal of reducing 1998 emission standards by 75% by achieving 99.5% reduction. Carbon monoxide (CO) emissions will be <1 ppm, non-methane hydrocarbon (NMHC) emissions will be <0.05 g/hp-hr, and oxides of nitrogen (NO_x) will be <0.15 g/hp-hr.
- Maintain or enhance current vehicle driveability by effective selection, matching, and configuring of off-the-shelf components.
- Maintain thermal efficiency of greater than 35%.
- Prove and enhance the engine design through in-service testing.
- Develop a public/private partnership to implement a commercialization plan that will bring new business and economic opportunities to Nevada.

Approach

- Use hydrogen added to the natural gas fuel mixture to achieve high charge dilution ratios to create near-zero NO_x emissions.
- Incorporate an alternative engine design from that of current heavy-duty engines which includes:
  - Nickel silicon carbide cylinder bores
  - Quiescent combustion
  - Higher rpm operation
  - Larger displacement
  - Mass air flow engine control

Accomplishments

- Demonstrated 0.22 g/hp-hr NO_x simulated driving cycle emissions
- Produced equivalent power and torque to natural gas engine
- Demonstrated 36% engine efficiency

Future Directions

- Expand the work to convert five additional City of Las Vegas Buses to HCNG

Introduction

The use of hydrogen as a fuel additive to extend the lean burn limit of conventional fuels has been repeatedly demonstrated to be a viable approach to achieving near-zero exhaust emissions from internal combustion engines. This technology is intended to be a near-term application for hydrogen and hydrogen infrastructure development given the current economic climate. Hydrogen fuel-related problems such as high fuel cost, high prime mover costs (fuel cells) and low energy density are largely overcome by supplementing natural gas, with hydrogen and using it in low-cost internal combustion engines.

Although lean-burn has been widely accepted as a viable approach to lowering exhaust emissions, achieving it with conventional fuels has not been as successful as exhaust catalyst systems. Finding the best application for hydrogen-supplemented lean-burn technology depends greatly on the nature of the engine loads and the standards used to test for exhaust emissions.

A significant philosophical difference between lean-burn and catalysts for controlling exhaust emissions is that lean-burn does not create the pollutants while catalysts chemically convert them. Understanding this basic difference is the key to recognizing the relative merits of each approach. Because pollutants are not created using the lean-burn technology, the types and frequency of engine loads are inconsequential to emission levels. With catalyst systems, the temperature of the catalyst is extremely important in determining the efficiency of emissions control. When catalyst temperatures are too low, as exists when a vehicle is first started, catalyst efficiency is poor. When catalyst temperatures are too high, the catalyst is degraded. Both scenarios result in high exhaust emissions. Therefore, engine loading and the frequency of those loads are very important in determining how catalyst systems work because they affect catalyst temperature. Given this technology base, heavy-duty transportation is the area where hydrogen-supplemented natural gas utilizing high charge dilution strategies can have the most significant impact on urban air quality.

Producing ultra-low exhaust emissions from heavy-duty vehicles differs markedly from that of light-duty vehicles. The most significant reason for this difference has to do with the relative power-to-weight ratios between the two. Light-duty engines typically produce much more ultimate power than is required by the emissions certification driving test. On the other hand, the engines used in heavy-duty applications typically are operated at their maximum power level most of the time, and the heavy-duty emissions test mirrors that use. Where this impacts emissions reduction technology is the effect that charge dilution (adding excess gases to the air-fuel mixture over what is required for stoichiometric combustion) has on engine power.

Charge dilution, whether it be excess air (lean-burn) or recirculated exhaust gases (EGR) or a combination of the two, is an extremely effective method of producing very low NO_x emissions. The support of complete combustion under these extreme charge diluted conditions is the rationale for using hydrogen in the fuel mix. The disadvantage to charge dilution is the reduction in the engine's maximum power output. This reduction in maximum power is the key to understanding why emissions control between light-duty and heavy-duty applications are significantly different.

The most effective way to recuperate lost engine power is to move more air through the engine. This is typically achieved by super/turbocharging or increasing engine rotational speed. Both of these techniques are readily implemented into light-duty engines. However, for heavy-duty engines, these techniques are not necessarily viable solutions. In the first place, heavy-duty engines are already turbocharged with significant levels of boost pressure to achieve high brake mean effective pressure (BMEP) at low rpm. Secondly, they are not readily adaptable to increased engine speed due to their extremely high reciprocating mass and low bore-to-stroke ratios. Therefore, using extremely high boost pressures (~ 2-3 bar) with existing heavy-duty engines would create large parasitic loads and reduce fuel efficiency. Increasing engine speed on these heavy pieces would seriously compromise reliability. These observations along with the fact that heavy-duty engines operate a great deal at maximum output, creates a serious problem for using charge dilution as a technique for lowering heavy-duty vehicle emissions with existing engine platforms.

The solution to this problem is to create an alternative engine platform that is designed for high charge dilution with the ability to produce power characteristics equivalent to those of current engines. Equivalent power characteristics are an important consideration. Not only is maximum engine power output important, but the maximum engine torque and the rpm for maximum torque are also important.

Approach

NRG Technologies, Inc. is using charge dilution as the mechanism for controlling harmful exhaust emissions. The basic technique employed is to combine EGR and lean-burn. Cooled and dried EGR will be used to control NO_x emissions, and lean-burn will be employed to control CO and NMHC emissions. It is anticipated that lean-burn will be employed to achieve approximately 2 to 4% oxygen in the exhaust. This will allow an off-the-shelf oxidizing catalyst to achieve very high conversion rates for both CO and NMHC emissions. Because the exhaust gas temperatures will be comparatively very low (<1000^{o}F), catalyst lifetime will be extremely high (>100,000 miles).

To achieve near-zero NO_x emissions, (10 to 20 ppm) using charge dilution, the engine must operate with an overall lambda (including EGR) of between 1.8 and 2.0. To achieve this value, at least 30%, by volume, of the fuel must be hydrogen. Any less than that will not support sufficiently consistent combustion from cylinder-to-cylinder or from cycle-to-cycle. Any attempts to achieve this through mechanical means (high turbulence combustion chambers, etc.) will result in (1) loss of engine efficiency through increased combustion chamber heat transfer rates and (2) increased NO_x emissions compared to "quiescent" or open combustion chambers and hydrogen addition to the fuel. The result is that mechanical enhancement (swirl, tumble, etc.) for lean-burn will require higher values of lambda to achieve equivalent NO_x emissions to that achieved by hydrogen-enhanced fuel.

Given the constraints for modifying existing heavy-duty engines, NRG proposes to develop an engine platform specifically-designed for high charge dilution that will create the same power characteristics to the rear wheels as the original natural gas or diesel engine. This is accomplished as follows:

- Large displacement engine:
  - An 8.8L V8 engine
- Turbocharging to increase BMEP
- Increased engine speed with gear reduction:
  - Using 8 cylinders rather than 6 allows greater engine rpm for the same engine displacement.
  - A gearset mounted on the rear of the engine to match the torque and speed characteristics of the original natural gas or diesel engine. The existing transmission can be retained.

The main drawback to NRG's approach will be the tendency to increase the frictional horsepower of the engine. All other things being equal, this will result in increased fuel consumption. There are many ways to combat this problem. They include the following:

- Higher values of lambda result in higher thermodynamic performance.
- Ratio of specific heats is higher which results in higher theoretical Otto Cycle efficiency.
- Very light valve train utilizing low spring pressure valve springs and low friction components (roller rockers and lifters).
- Cylinder coatings with low friction coefficients.
- Nickel-Silicon Carbide (currently used by BMW, Mercedes, and Porsche).

The overall engine package is controlled by an engine control module. The same basic package that NRG has used for electronic fuel, ignition, and actuator controls on all of their light-duty vehicles will also be used for this heavy-duty engine.

The test project will include the evaluation of exhaust emissions, engine performance, engine reliability, and vehicle performance. During Phase I, exhaust emissions were verified using a steady-state simulation of the Federal Driving Test. For Phase II of the project, emissions will be verified by a vehicle driving test conducted at CAVTEC, an independent testing laboratory in Oakland, CA. For the on-the-road testing to be conducted in Las Vegas, an on-board data acquisition system (Campbell Scientific) with cell phone access will be installed on the bus. The measurements anticipated to be monitored include:

- Engine oil, water, and intake air temperatures
- Turbocharger boost pressure
- Engine rpm
- Throttle position
- Vehicle speed

Fuel economy will be measured using records of gas usage vs. bus mileage.

The maintenance program for Phase II will include:

- Periodic oil analysis
- Training of city personnel for:
  - Engine oil usage
  - Gearbox oil usage
  - Filter replacements
  - Gearbox troubleshooting

Results

A 30-ft. transit bus was purchased by DOE and shipped to NRG Tech for conversion to HCNG operation. This bus came equipped with a Cummins 8.3L natural gas engine. The project called for characterizing the exhaust emissions from the current configuration so that the benefits of HCNG can be quantitatively assessed. Baseline exhaust emissions were taken from the engine using a steady-state emissions test protocol that is designed to simulate the heavy-duty driving test procedure. This protocol is as follows:

Engine rpm at Maximum Torque Value

Test Point 1	100% load	Emissions are 15% of weighted value
Test Point 2	75% load	Emissions are 15% of weighted value
Test Point 3	50% load	Emissions are 15% of weighted value
Test Point 4	10% load	Emissions are 10% of weighted value

Engine rpm at Maximum Power Value

Test Point 5	100% power	Emissions are 10% of weighted value
Test Point 6	75% power	Emissions are 10% of weighted value
Test Point 7	50% power	Emissions are 10% of weighted value
Test Point 8	Idle	Emissions are 15% of weighted value

The results of testing the Cummins engine that was installed in this bus using the protocol listed above are shown in Table 1.

Emissions results for the 8.8L NRG engine using the same testing protocol and using a 30/70 mixture of hydrogen and natural gas are shown in Table 2.

The final configuration for the 8.8L NRG engine consists of the following:

- 8.8L aluminum V8 engine
- Nickel-silicon carbide coated cylinder sleeves
- DIS ignition system
- Fuel injection system with feedback control
- Fully computer-controlled engine management system

Conclusions

Emissions, power, torque, and efficiency goals have been met. NO_x emissions have been reduced by a factor of 20 when compared to the existing engine without a loss of power, torque characteristics, or fuel efficiency. Major milestones for the remainder of the project will be to demonstrate drivability in an operating bus and verify exhaust emissions in a driving test.

Table 1. 8 Mode Steady State Emissions Summary
Cummins 8.3L Natural Gas Engine (as received)

Individual Modes	NOx g/hp-hr	THC g/hp-hr	NMHC (g/hp-hr)	CO g/hp-hr	Weighting Factor
1400 rpm - 100% Load	7.42	5.21	0.16	0.19	0.15
- 75% Load	4.70	2.57	0.08	0.22	0.15
- 50% Load	5.67	3.37	0.10	0.25	0.15
- 10% Load	5.77	7.70	0.23	0.59	0.10
2400 rpm - 100% Load	1.18	2.82	0.08	0.28	0.10
- 75% Load	0.80	4.26	0.13	0.32	0.10
- 50% Load	0.44	5.56	0.17	0.37	0.10
800 rpm - Idle	6.96	107.74	3.23	12.98	0.15
Weighted 8 Mode (g/hp-hr)	4.60	19.87	0.58	2.20	
Weighted 8 Mode (g/kw-hr)	6.16	26.63	0.78	2.95	

Table 2. 8 Mode Steady State Emissions Summary
NRG Hydrogen-Enriched Natural Gas Bus Engine

Individual Modes	NOx g/hp-hr	THC g/hp-hr	NMHC (g/hp-hr)	CO g/hp-hr	Weighting Factor
1800 rpm - 100% Load	0.37	3.70	0.07	0.00	0.15
- 75% Load	0.20	5.80	0.10	0.00	0.15
- 50% Load	0.10	5.48	0.10	0.00	0.15
- 10% Load	0.25	5.10	0.10	0.00	0.10
2800 rpm - 100% Load	0.10	5.63	0.26	0.00	0.10
- 75% Load	0.09	4.71	0.19	0.00	0.10
- 50% Load	0.11	6.01	0.26	0.00	0.10
800 rpm - Idle	0.40	17.44	0.36	0.00	0.15
Weighted 8 Mode (g/hp-hr)	0.22	7.00	0.18	0.00	
Weighted 8 Mode (g/kw-hr)	0.29	9.38	0.24	0.00	