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ADVANCED INTERNAL COMBUSTION ELECTRICAL GENERATOR

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Abstract

In this paper, research on hydrogen internal combustion engines is discussed. The objective of this project is to provide a high-efficiency means of renewable hydrogen-based fuel utilization. The development of a high-efficiency, low-emissions electrical generator will lead to establishing a path for renewable hydrogen-based fuel utilization. A full-scale prototype will be produced in collaboration with industrial partners.

The electrical generator is based on developed internal combustion reciprocating engine technology. It is able to operate on many hydrogen-containing fuels. The efficiency and emissions are comparable to fuel cells (50% fuel to electricity, ~ 0 NO_x). This electrical generator is applicable to both stationary power and hybrid vehicles. It also allows specific markets to utilize hydrogen economically.

Introduction

Two motivators for the use of hydrogen as an energy carrier today are 1) to provide a transition strategy from hydrocarbon fuels to a carbonless society, and 2) to enable renewable energy sources. The first motivation requires a little discussion while the second one is self-evident. The most common and cost-effective way to produce hydrogen today is the reformation of hydrocarbon fuels specifically natural gas. Robert Williams discusses the cost and viability of natural gas reformation with CO_2 sequestration as a cost-effective way to reduce our annual CO_2 emission levels. He argues that if a hydrogen economy was in place then the additional cost of natural gas reformation and subsequent CO_2 sequestration is minimal (Williams 1996). Decarbonization of fossil fuels with subsequent CO_2 sequestration to reduce or eliminate our CO_2 atmospheric emissions provides a transition strategy to a renewable, sustainable, carbonless society. However, this requires hydrogen as an energy carrier.

The objectives of this program for the year 2001 are to continue to design, build, and test the advanced electrical generator components, research hydrogen-based renewable fuels, and develop industrial partnerships. The rationale behind the continuation of designing, building, and testing generator components is to produce a research prototype for demonstration in three years. Similarly, researching hydrogen-based renewable fuels will provide utilization components for the largest possible application. Finally, developing industrial partnerships can lead to the transfer of technology to the commercial sector as rapidly as possible.

This year work is being done on the linear alternator; two-stroke cycle scavenging system, electromagnetic/combustion/dynamic modeling, and fuel research. The Sandia alternator design and prototype will be finished, and the Magnequench design will be tested. Work on the scavenging system consists of using KIVA-3V to investigate loop and uniflow configurations. Ron Moses of Los Alamos National Laboratories is conducting the modeling; modeling of the alternator is being performed. Hydrogen-based renewables, such as biogas and ammonia, are the fuels being researched. Outside of modeling and research, an industrial collaboration has been made with Caterpillar, Unique Mobility and Magnequench International, a major supplier of rare earth permanent magnet materials.

Background

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 IC 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, while the fuel cell enjoys high public relations appeal, it seems possible that it may not offer significant efficiency advantages relative to an optimized combustion system. In light of these factors, the capabilities of internal combustion engines have been reviewed.

In regards to thermodynamic efficiency, the Otto cycle theoretically represents the best option for an IC engine cycle. This is due to the fact that the fuel energy is converted to heat at constant volume when the working fluid is at maximum compression. This combustion condition leads to the highest possible peak temperatures, and thus the highest possible thermal efficiencies.

Edson (1964) analytically investigated the efficiency potential of the ideal Otto cycle using compression ratios (CR) up to 300:1, where the effects of chemical dissociation, working fluid thermodynamic properties, and chemical species concentration were included. He found that even as the compression ratio is increased to 300:1, the thermal efficiency still increases for all of the fuels investigated. At this extreme operating for instance, the cycle efficiency for isooctane fuel at stoichiometric ratio is over 80%.

Indeed it appears that no fundamental limit exists to achieving high efficiency from an internal combustion engine cycle. However, many engineering challenges are involved in approaching ideal Otto cycle performance in real systems, especially where high compression ratios are utilized.

Caris and Nelson (1959) investigated the use of high compression ratios for improving the thermal efficiency of a production V8 spark ignition engine. They found that operation at compression ratios above about 17:1 did not continue to improve the thermal efficiency in their configuration. They concluded that this was due to the problem of non-constant volume combustion, as time is required to propagate the spark-ignited flame.

In addition to the problem of burn duration, other barriers exist. These include the transfer of heat energy from the combustion gases to the cylinder walls, as well as the operating difficulties associated with increased pressure levels for engines configured to compression ratios above 25:1 (Overington and Thring 1981, Muranaka and Ishida 1987). Still, finite burn duration remains the fundamental challenge to using high compression ratios.

The goal of emissions compliance further restricts the design possibilities for an optimized IC engine. For example, in order to eliminate the production of nitrogen oxides (NO_x), the fuel/air mixture must be homogeneous and very lean at the time of combustion (Das 1990, Van Blarigan 1995). (It is subsequently possible to use oxidation catalyst technologies to sufficiently control other regulated emissions such as HC and CO.) Homogeneous operation precludes diesel-type combustion, and spark-ignition operation on premixed charges tends to limit the operating compression ratio due to uncontrolled autoignition, or knock. As well, very lean fuel/air mixtures are difficult, or impossible, to spark-ignite.

On the other hand, lean charges have more favorable specific heat ratios relative to stoichiometric mixtures, and this leads to improved cycle thermal efficiencies. Equivalence ratio is no longer required to be precisely controlled, as is required in conventional stoichiometric operation when utilizing three way catalysts. Equivalence ratio is defined here as the ratio of the actual fuel/air ratio to the stoichiometric ratio.

Combustion Approach

Homogeneous charge compression ignition combustion (HCCI) could be used to solve the problems of burn duration and allow ideal Otto cycle operation to be more closely approached. In this combustion process a homogeneous charge of fuel and air is compression heated to the point of autoignition. Numerous ignition points throughout the mixture can ensure very rapid combustion (Onishi et al 1979). Very low equivalence ratios ($\phi \sim 0.3$) can be used since no flame propagation is required. Further, the useful compression ratio can be increased, as higher temperatures are required to autoignite weak mixtures (Karim and Watson 1971).

HCCI operation is unconventional, but is not new. As early as 1957 Alperstein et al. (1958) experimented with premixed charges of hexane and air, and n-heptane and air in a Diesel engine. They found that under certain operating conditions their single-cylinder engine would run quite well in a premixed mode with no fuel injection whatsoever.

In general, HCCI combustion has been shown to be faster than spark ignition (SI) or compression ignition combustion. And much leaner operation is possible than in SI engines, while lower NO_x emissions result.

Most of the HCCI studies to date however, have concentrated on achieving smooth releases of energy under conventional compression condition (CR ~ 9:1). Crankshaft-driven pistons have been utilized in all of these previous investigations. Because of these operating parameters, successful HCCI operation has required extensive exhaust gas recirculation (EGR) and/or intake air preheating. Conventional pressure profiles have resulted (Thring 1989, Najt and Foster 1983).

In order to maximize the efficiency potential of HCCI operation, much higher compression ratios must be used and a very rapid combustion event must be achieved. Recent work with higher compression ratios (~21:1) has demonstrated the high efficiency potential of the HCCI process (Christensen et al 1998, Christensen et al 1997).

In Figure 1, the amount of work attained from a modern 4-stroke heavy-duty diesel engine is shown at a 16.25:1 compression ratio. The results show that under ideal Otto cycle conditions (constant volume combustion), 56% more work is still available. This extreme case of non-ideal Otto cycle behavior serves to emphasize how much can be gained by approaching constant volume combustion.

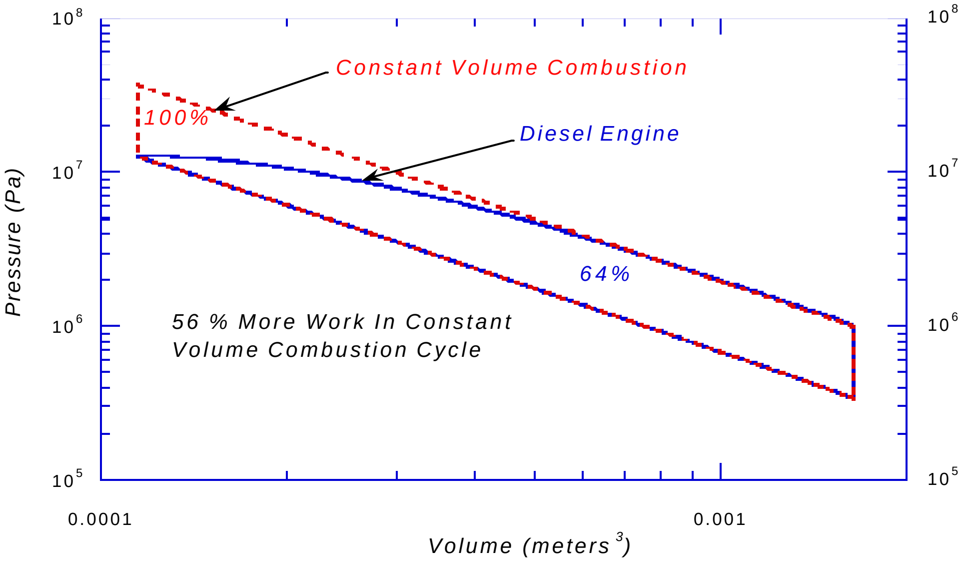


Figure 1 – Modern 4-Stroke Heavy Duty Diesel Engine

Engineering Configuration

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

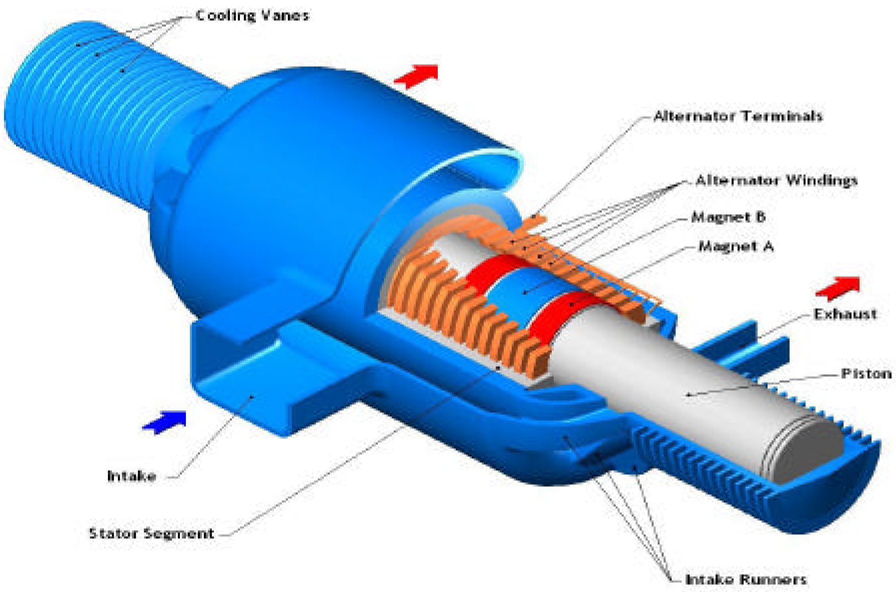


Figure 2 – Free piston linear alternator

The linear generator is designed such that electricity is generated directly from the piston's oscillating motion, as rare earth permanent magnets fixed to the piston are driven back and forth through the alternator's coils. 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, by efficiently managing the piston's kinetic energy through each stroke. 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 use of free pistons in internal combustion engines has been investigated for quite some time. In the 1950's, experiments were conducted with free piston engines in automotive applications. In these early designs, the engine was used as a gasifier for a single stage turbine (Underwood 1957, Klotsch 1959). More recent developments have integrated hydraulic pumps into the engine's design (Baruah 1988, Achten 1994).

Several advantages have been noted for free piston IC engines. First, the compression ratio of the engine is variable; this is dependent mainly on the engine's operating conditions (e.g., fuel type, equivalence ratio, temperature, etc.). As a result, the desired compression ratio can be achieved through modification of the operating parameters, as opposed to changes in the engine's hardware.

An additional benefit is that the mechanical friction can be reduced relative to crankshaft-driven geometries since there is only one moving engine part and no piston side loads. Also, combustion seems to be faster than in conventional slider-crank configurations. Further, the unique piston dynamics (characteristically non-sinusoidal) seem to improve the engine's fuel economy and NO_x emissions by limiting the time that the combustion gases spend at top dead center (TDC) (thereby reducing engine heat transfer and limiting the NO_x kinetics). Finally, one researcher (Braun 1973) reports that the cylinder/piston/ring wear characteristics are superior to slider/crank configurations by a factor of 4.

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. The following advantages should be found:

1. For a given maximum piston velocity, the free piston arrangement is capable of achieving a desired compression ratio more quickly than a crankshaft-driven piston configuration. This point is illustrated in Figure 3 where the piston position profiles of both configurations are plotted. The reduced compression time should result in higher compression of the premixed charge before the onset of autoignition.

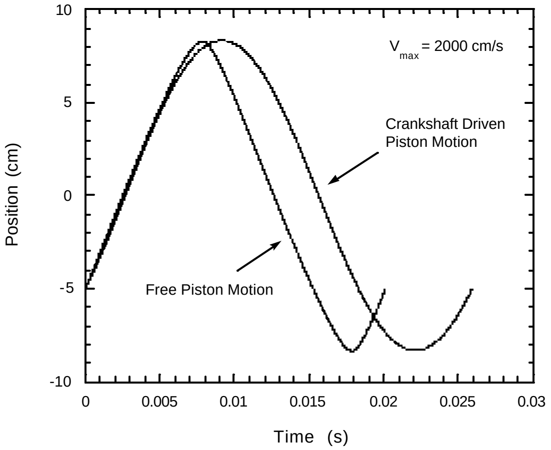


Figure 3 – Piston position vs. time

2. High compression ratio operation is better suited to the free piston engine since the piston develops compression inertially, and as such there are no bearings or kinematic constraints that must survive high cylinder pressures or the high rates of pressure increase (shock). The use of low equivalence ratios in the HCCI application should further reduce the possibility of combustion chamber surface destruction (Lee and Schaefer 1983, Maly et al 1990).

3. The free piston design is more capable of supporting the low indicated mean effective pressure (IMEP) levels inherent in low equivalence ratio operation due to the reduction in mechanical friction.

Integration of the linear alternator into the free piston geometry provides further benefits to the generator design. In this arrangement mechanical losses in the system are dramatically reduced since there is essentially one moving part, and this allows engine operation at a more or less constant piston speed. These points aid in the generator design, and further improve the fuel-to-electricity generation efficiency of the device.

The linear alternator itself is based on technology developed for brushless DC motors. High efficiency and high power density, typically 96% efficiency and 1 hp per pound density characterize this class of motors. Put simply, the rotary configuration is unrolled until flat, then rolled back up perpendicular to the first unrolling to arrive at the linear configuration. Relative to the rotary geometry, the linear device is approximately 30% heavier due to not all of the coils being driven at the same time. Efficiency will be comparable.

2-Stroke Cycle

Inherent in the configuration selected is the need to scavenge the exhaust gases out of the cylinder and replace them with fresh fuel/air charge while the piston is down at the bottom of the cylinder. This requirement is due to the need to have trapped gases in the cylinder to act as a spring, as well as to provide the next combustion event.

Conventional 2-stroke cycle engines have developed a reputation for low fuel efficiency and high hydrocarbon emissions due to short-circuiting of the inlet fuel/air mixture directly to the exhaust port. The typical 2-stroke application stresses power density over efficiency and emissions – chain saws, weed whackers, marine outboard motors. These devices must operate over a wide speed and power range.

In this case the requirements are quite different. The speed of the free piston oscillation is essentially fixed. Power is varied by modification of the equivalence ratio, not the quantity of gas delivered. Power density is not a driving requirement. As a result, the design of this system can be optimized within tight constraints utilizing computational fluid dynamics and experimental gas dynamics techniques.

Experimental Results - FY 2001

Figure 4 shows the results of experimental combustion studies completed with hydrogen. In this investigation, a single-stroke rapid compression-expansion machine has been used to compression-ignite hydrogen. Hydrogen is the fastest burning fuel out of all the fuels tested. The high rate of combustion does approach constant volume combustion. Figure 3 shows a typical logarithmic P/V diagram for hydrogen combustion at top dead center at 33:1 compression ratio. The piston has, for all practical purposes, not moved 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. Additionally, operation at equivalence ratios less than 0.5 reduces the need to consider piston erosion, or other physical damage (Maly et al. 1990).

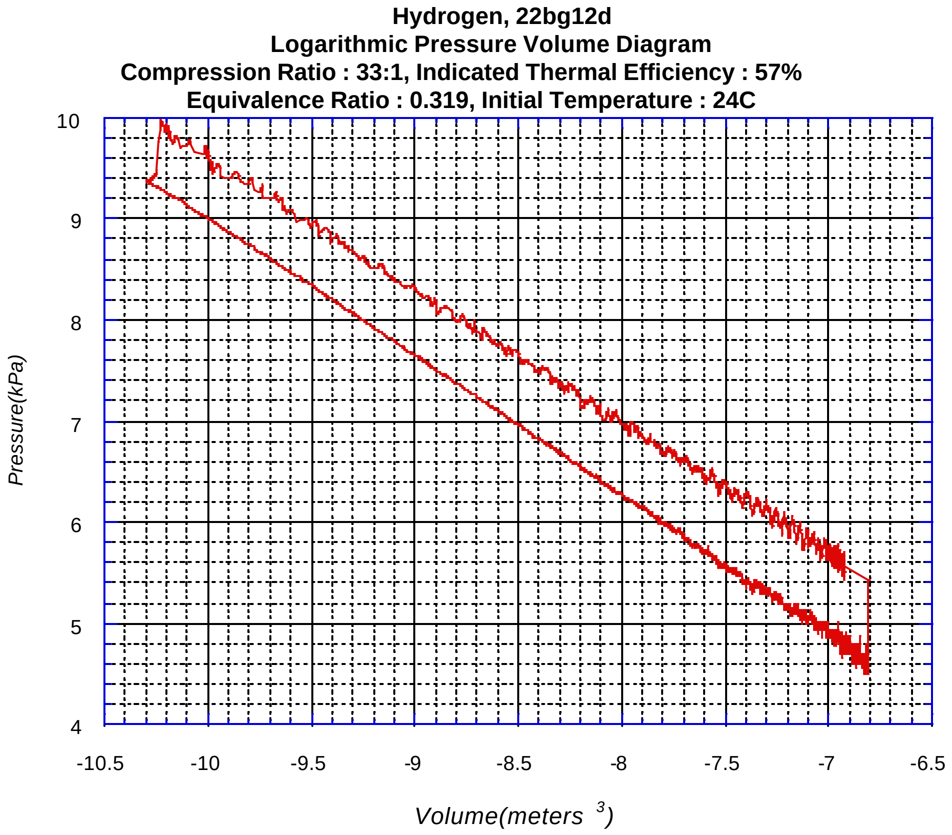


Figure 4 - Hydrogen Combustion

Figure 5 shows the free piston generator again. The overall length of the generator is 76 centimeters, its specific power is 800 watts per kilogram, and it has a power density of 800 watts per liter. Hydrogen based renewable fuels such as biogas (low BTU producer gas H_2-CH_4-CO); ammonia (NH_3), methanol (CH_4O), and/or hydrogen (H_2) can be used directly.

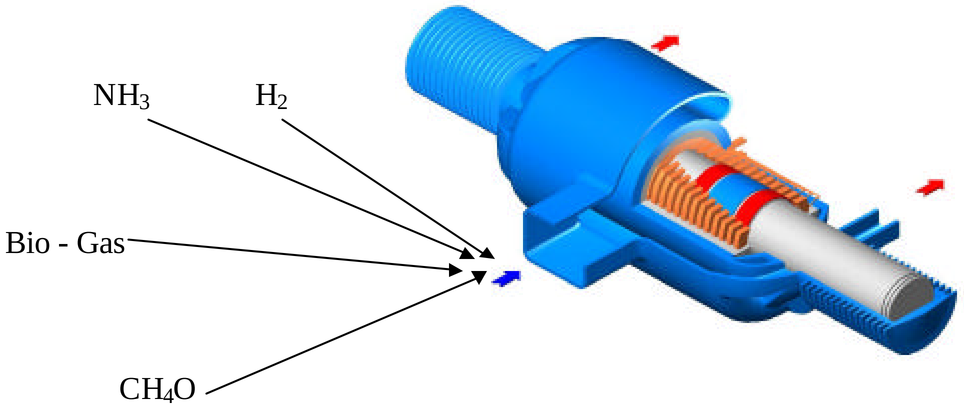


Figure 5 – Free Piston Generator

The alternator consists of moving rare earth permanent magnets and stationary output coils and stator laminations. The design is similar to a conventional rotary brushless DC generator.

Figure 6 shows the magnetic flux path for the linear alternator. It can be seen that the flux through the coils changes direction as the permanent magnet assembly moves down the alternator core. This changing flux induces current in the coils.

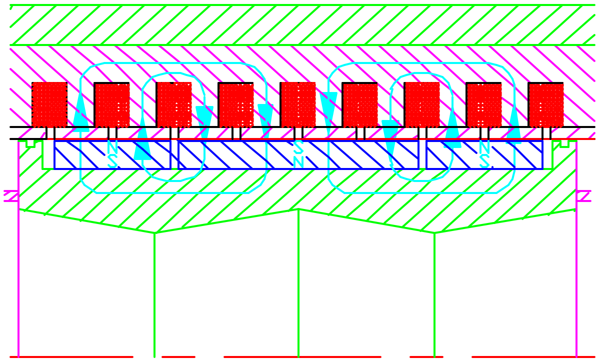


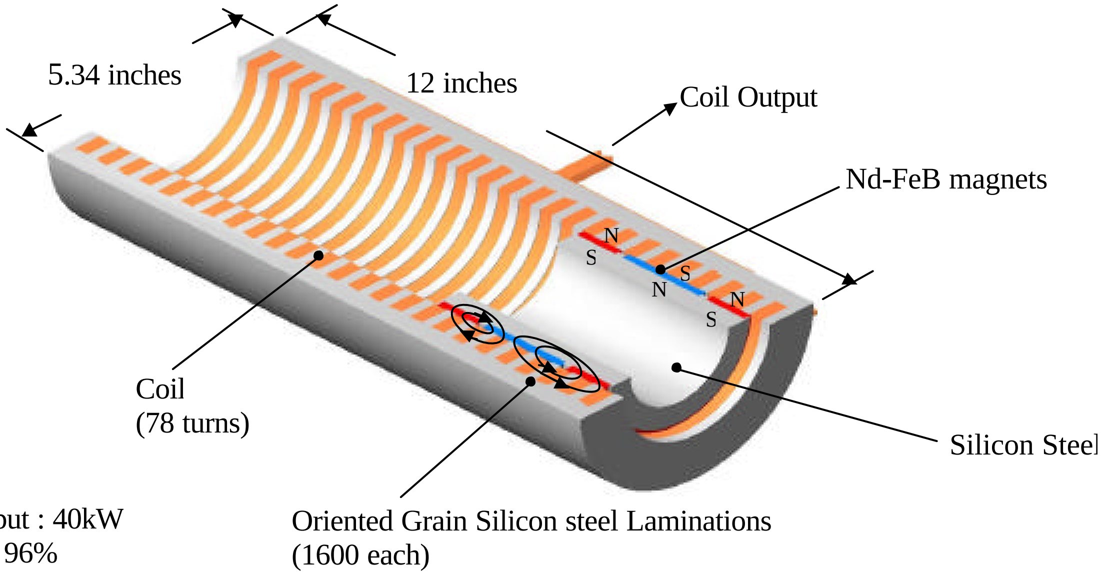
Figure 6 – Alternator Design

Two parallel paths are being pursued to develop the linear alternator. An alternator is being built and tested in-house. As a design tool, we are utilizing a two-dimensional finite element computer code to solve Maxwell’s equations of electromagnetism. MagSoft Corporation produces the code, called FLUX2D. We have investigated various design configurations, and have optimized a design with respect to maximizing efficiency and minimizing size. In parallel, Magnequench, a commercial development partner, is also designing and fabricating an alternator. Both alternator designs are being fabricated and will be tested under full design output conditions on a Sandia designed-Caterpillar engine based tester. The tester will measure both power output and mechanical to electrical conversion efficiency.

Magnequench has delivered three stator assemblies to Sandia, one of which is shown in Figure 7. Also shown in Figure 7 are a short and a long magnet ring. These magnets are pressed from neodymium-iron-boron rare earth material and magnetized in the radial direction. Sandia will assemble the Magnequench supplied magnets to the moving part back iron and provide linear bearing supports. One assembly will then be returned to Magnequench for their own testing.

Figure 8 shows a cut away of the Sandia alternator design. The power output of the linear alternator is 40 kW, and has an efficiency of 96%. The Magnequench design is very similar; the differences are primarily in the coil configuration, magnet fabrication and stator material. The Sandia magnet assembly is fabricated from 10-degree arc magnet segments, which are magnetized in a linear direction

Figure 7 – Magnequench Linear Alternator Stator Assembly



Power Output : 40kW
Efficiency: 96%
Weight 60 pounds

Figure 8 – Sandia Linear Alternator Design

The Sandia stator is an assembly of 1600 laminations punched from anisotropic oriented grain silicon steel. Each lamination has a small angle ground so the assembly stacks into a cylinder. The Magnequench stator material is pressed iron powder in an adhesive matrix.

The Magnequench coils consist of a single row winding of flat wire. The Sandia coils contain 78 turns of square cross section wire. The Magnequench coils must be connected in moving groups of five as the magnet assembly moves in the stator to generate sufficient voltage for efficient power conditioning. The Sandia design has sufficient voltage generation from a single coil and does not require coil switching.

During initial assembly of the Sandia stator laminations to the coils some electrical shorting of the coils to the stator was discovered. Investigation revealed that the wire insulation was being cut by the sharp stator laminations and that the 0.003-inch thick kapton insulation on the coil sides was not robust enough to withstand assembly handling. As a result we are currently modeling larger coil spaces in the stator pieces and smaller coils to determine the effect on alternator performance. Based on these analyses we will choose which part, the coil or the stator lamination, to modify.

Due to the difficulty of the Sandia design assembly, the Magnequench alternator will be the first to be tested on our full-power alternator tester. A mounting fixture, which supports the stator assembly on load cells, has been built and assembly procedures to align and zero the load cells are ongoing. As part of the mounting design the magnet assembly is being developed to be useful for assembly of the prototype engine generator. This assembly requires the development of an inertial weld between the aluminum pistons and the magnet backiron section, which is 1018 steel. Both 6061 and 7075 aluminum are being investigated for the piston material. To date sample welds of both materials have been completed and tooling to tensile test the welds is being fabricated. Some of the components and fabrication tools for the Sandia linear alternator are shown in Figure 9.

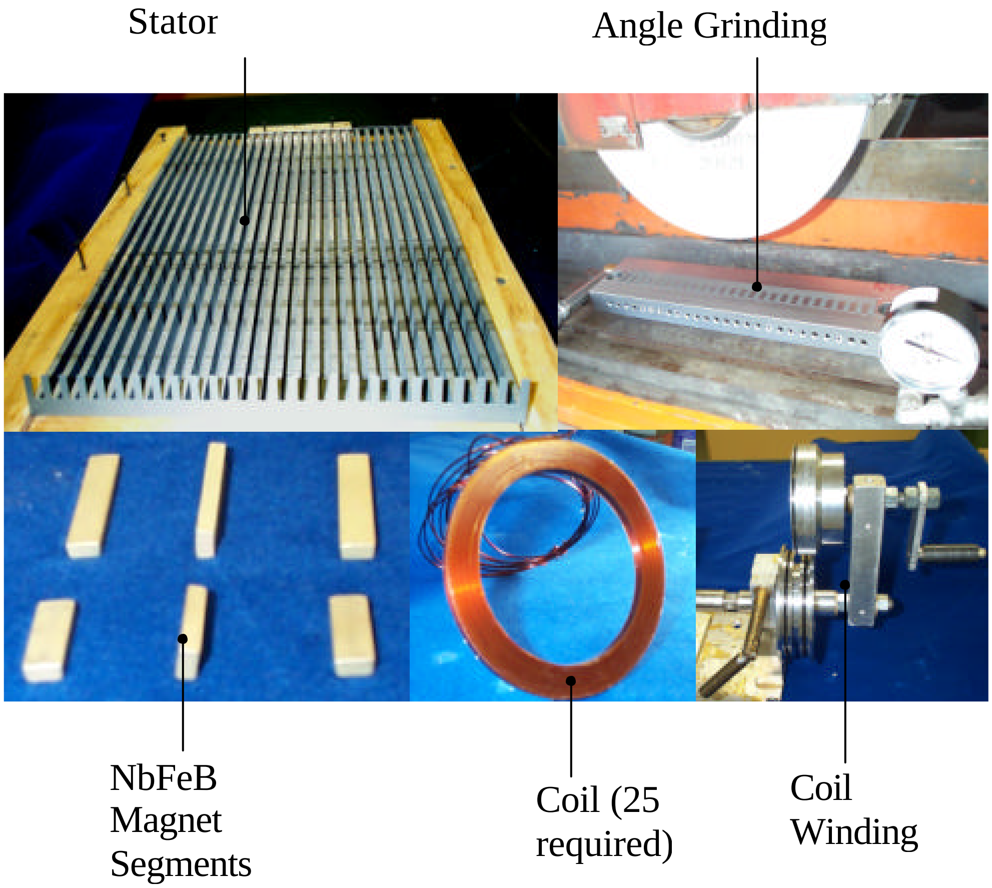


Figure 9 – Linear Alternator Design Components

Alternator Modeling

In preparation for designing the generator control algorithms, a comprehensive mathematical model of the entire physical system is required. One of the challenging aspects of the system model is the electromagnetic performance of the linear alternator. The finite element model (FLUX2D) utilized in the design process is too slow for use in a real-time system model.

To circumvent this situation, we have contracted with Ron Moses of Los Alamos National Laboratory to derive a simplified alternator model. Ron is an expert in electromagnetic systems and excited to be part of our project team. We intend to have Ron develop, with our input, a total system model capable of predicting control system response.

Two Stroke-Cycle Scavenging System Design

Conventional two-stroke cycle engines are designed to maximize power density at the expense of efficiency and emissions. They also must operate over a wide speed and power range.

Our design intent is to maximize efficiency while minimizing emissions at a narrow power output operating condition. As a result, the configuration of the scavenging ports and operating pressures is likely to be unique to this design.

Our approach is to utilize KIVA-3V to design the scavenging system and to validate the KIVA-3V predictions at selected conditions. Towards this goal we have designed an add-on scavenging experiment for our free piston combustion test facility. Figure 10 shows the scavenging experiment on the upper left side connected to the existing combustion experiment on the lower right side. The experiment will reproduce combustion cylinder pressure and temperature conditions immediately prior to scavenging port opening and replicate piston motion during one scavenging cycle. By measuring gases in the cylinder and in the exhaust collector we will be able to discern trapping efficiency and scavenging efficiency during realistic operating conditions.

Figure 11 shows the KIVA-3V modeling results for one particular configuration being investigated. We are striving to design a loop scavenged flow system due to the simplicity it possesses. This year we have analyzed two loop scavenged systems. The first system, shown above, is a conventional design with the exhaust port higher in the cylinder wall than the inlet ports. In this geometry the exhaust port opens first, with a significant quantity of exhaust gases blowing down before the inlet ports open. As the inlet ports open, flow is directed up and away from the exhaust port in an attempt to loop up into the cylinder and flush more exhaust out.

Parameters that were varied include inlet driving pressure, port placement and lead angles, and reciprocating speed. Briefly, the end results were that to avoid short circuiting more than 1% of the inlet flow to the exhaust, only about 50% of the exhaust gases can be removed. A major contributor to this situation was thought to be the placement of the inlet ports below the exhaust port.

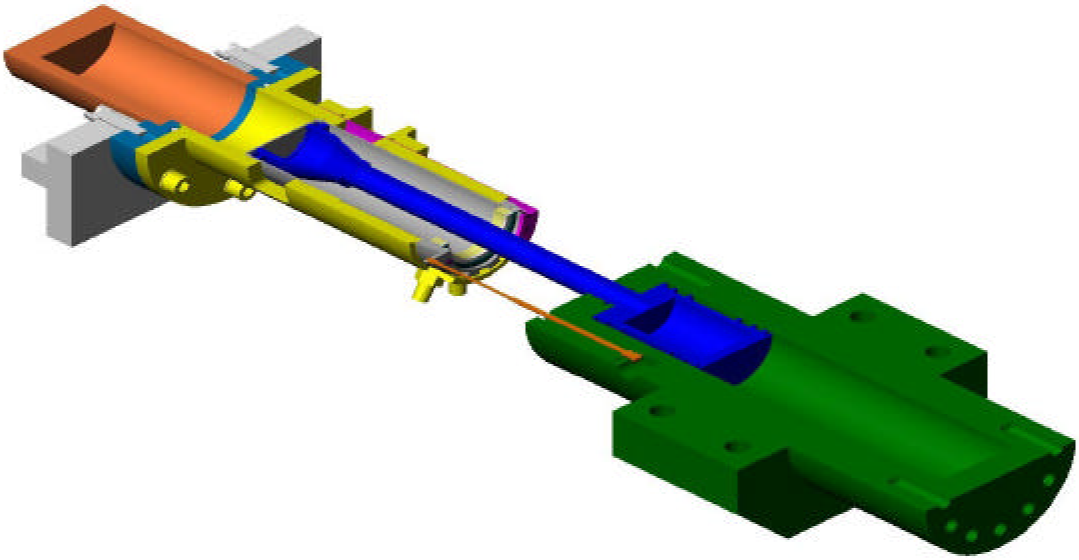


Figure 10 – Scavenging Experiment

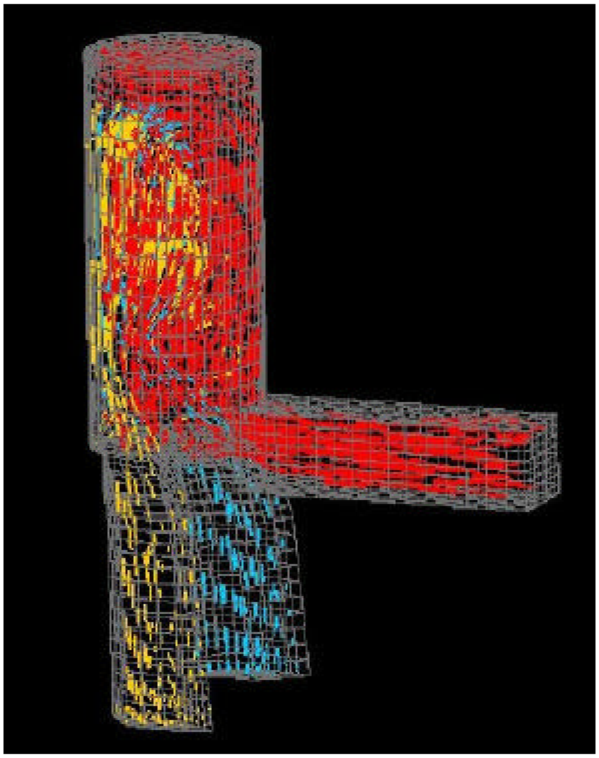


Figure 11 – KIVA-3V flow pictorial - loop

As a result a model was generated with the inlet ports above the exhaust port. Figure 12 shows this configuration. The goal was to generate a fluid motion that would sweep the exhaust gases up the outside of the cylinder and then flow down the center and out the exhaust ports.

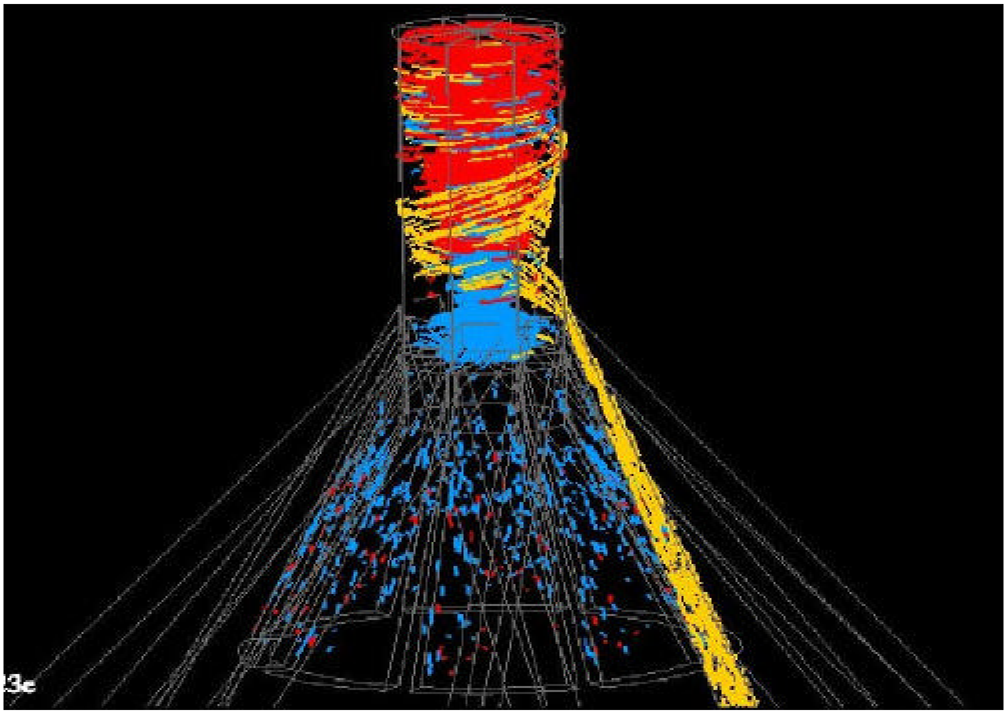


Figure 12 – KIVA-3V flow pictorial – inverted loop

KIVA calculations show the flow sweeping up the outside, but stagnating at the top of the cylinder and not flushing down the center. Part of the difficulty is the high stroke to bore ratio necessary to minimize heat losses and insure adequate compression space at high compression ratio. The results of the calculation show similar performance to the more conventional loop scavenged design.

We are currently designing a uniflow system with 4 exhaust valves in the cylinder head. Variation of the inlet flow geometry/driving pressure has resulted in a more acceptable 80% removal of the exhaust gases with less than 1% short-circuiting of the inlet flow. This configuration, shown in Figure 13 also allows variation of the exhaust port timing since these valves are controlled independently of the piston position. We have been able to consider overexpanded strokes and exhaust residual left at the cylinder head and on top of the piston. This can have the beneficial result of insulating the metal engine parts from the combustible mixture, thus minimizing heat losses and wall quenching.

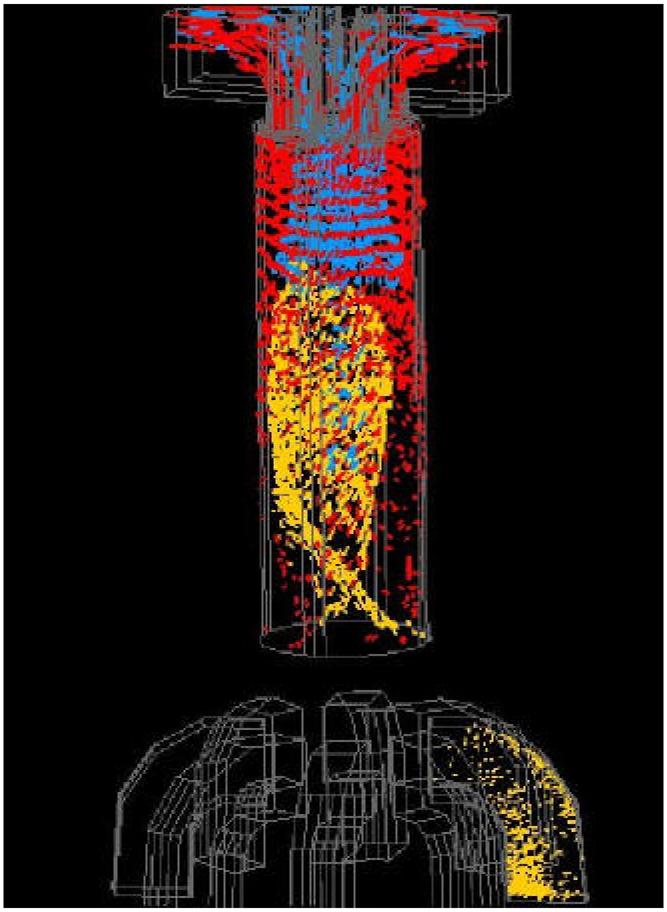


Figure 13 – KIVA-3V flow pictorial – uniflow

Currently the analytical scavenging investigation is centered on maximizing thermal efficiency considering scavenging blower work, overexpanded cycles and friction losses. Both constant pressure and piston motion driven type blowers are considered. Following this investigation the scavenging experiment will be fabricated and key-operating predictions verified.

Hydrogen Based Renewable Fuels

Bio-gas

One of the unique characteristics of HCCI combustion with a free piston is the ability to combust extremely lean mixtures. In the field of gasification of biomass, the simplest approach is to combust the material in an oxygen-starved environment. The resultant gas is a mixture of hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen. The mixture is too lean for utilization in spark-ignition engines and requires a pilot diesel fuel injection when fumigated into a diesel engine.

Figure 14 shows the results of combustion of a typical low BTU producer gas as would be produced from a crude gasifier as would be found in a developing country. The formulation was kindly supplied by William Hauserman of Hauserman Associates. The results indicate excellent performance in the free piston experiment. In fact, this lean mixture is ideal for achieving the NO_x control upon which our concept is based

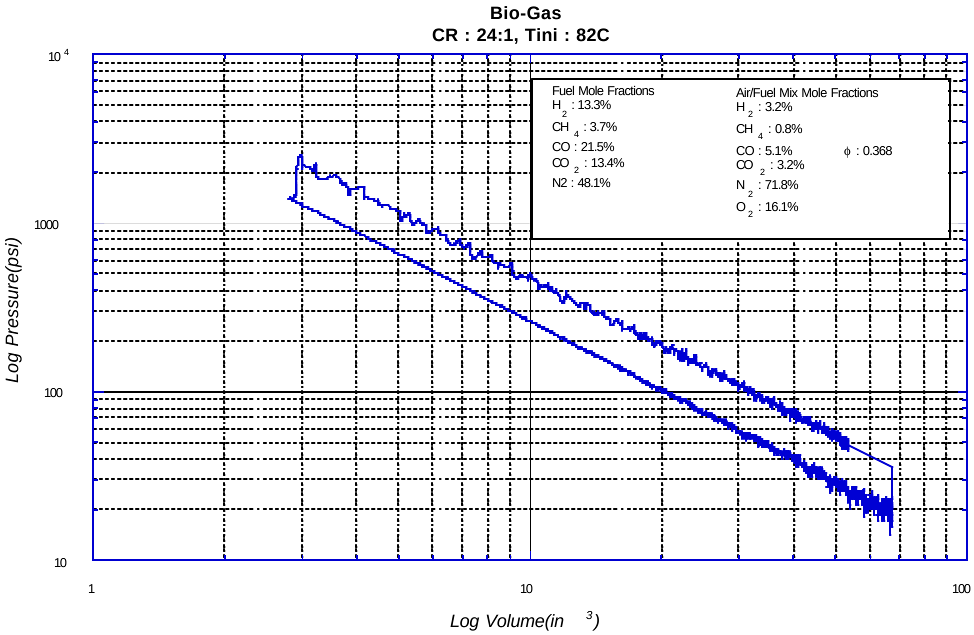


Figure 14 – Biogas Ideal Otto Cycle Performance

The two most challenging aspects of widespread hydrogen application are the storage of hydrogen for mobile applications and the distribution infrastructure. In the United States, approximately one million farms have access to anhydrous ammonia. The distribution infrastructure already exists to deliver approximately 8 billion pounds of anhydrous ammonia to these farms for direct use as a nitrogen soil supplement. The farmers are already handling anhydrous ammonia and could easily use it as a fuel for their farm equipment if an efficient utilization device were available.

In Figure 15, the combustion of ammonia exhibits ideal Otto cycle performance in our free piston combustion experiment, and produces conversion efficiencies comparable to hydrogen (see Figure 16). Ammonia is ideal hydrogen based renewable fuel to use in our free piston generator for several reasons. Ammonia is widely available. 35 trillion pounds of anhydrous ammonia are produced in the United States per year. Ammonia contains no carbon, and can be easily made from hydrogen or natural gas.

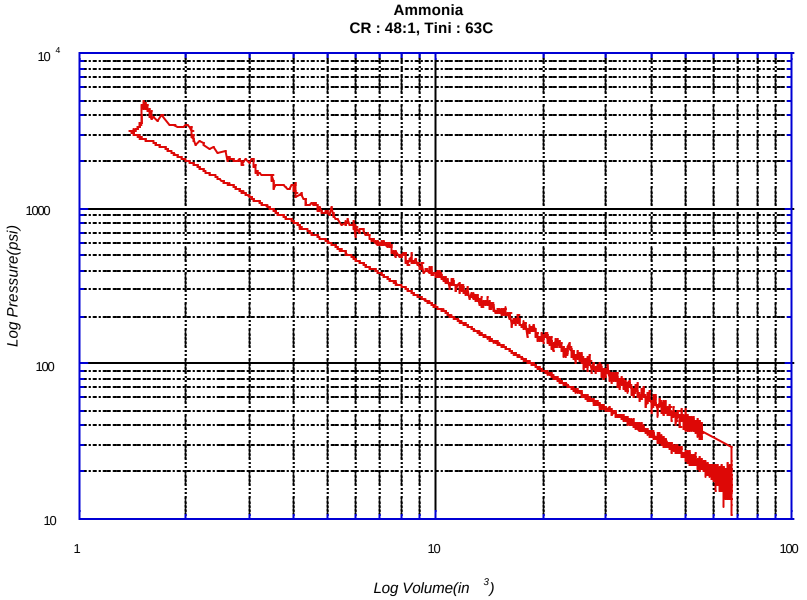


Figure 15 – Ammonia Ideal Otto Cycle Performance

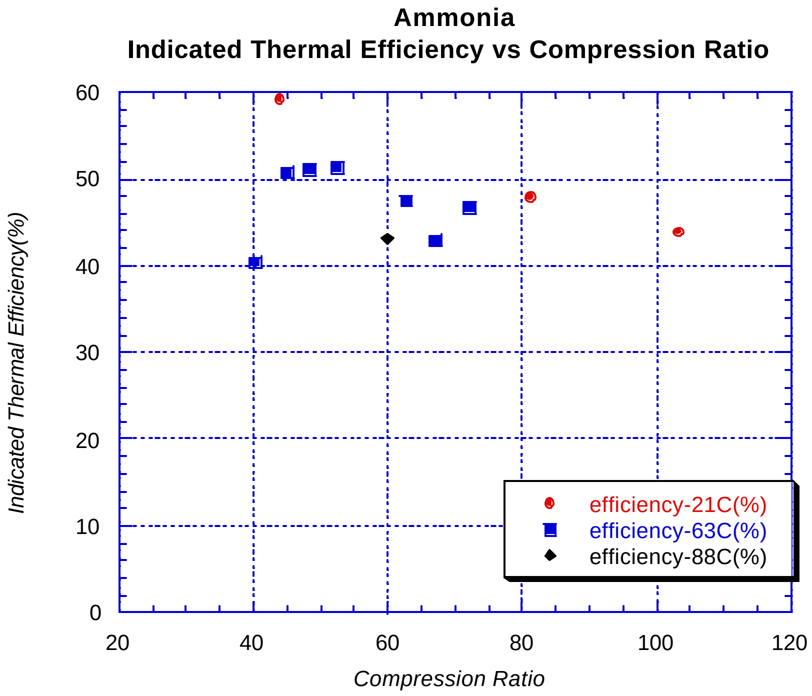


Figure 16 – Ammonia Combustion

Anhydrous ammonia is stored in the same manner as propane, as a liquid under approximately 100-psi vapor pressure at room temperature. If released into the atmosphere, ammonia's density is lighter than that of air and thus dissipates rapidly. In addition, because of its characteristic smell the nose easily detects it in concentrations as low as 5 ppm. Finally, ammonia has such a narrow flammability range that it is generally considered non-flammable when transported.

Ammonia is comparable to gasoline as a fuel for combustion engines. Three gallons of ammonia is equivalent to one gallon of gasoline in energy content. In other terms, 2.35 pounds of ammonia is equivalent to one pound of gasoline in energy content. Cost wise in 1998, bulk ammonia was $1.13 per gallon gasoline equivalent.

In using ammonia as a fuel, ammonia and air would enter the free piston generator through the intake port. After combustion, any generated NO_x emissions can be readily reduced by reaction with ammonia over a zeolite according to one of the following two reactions:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

Measurement of the ammonia and NOx emissions from typical operating conditions have shown approximately equal quantities (400ppm) of both ammonia and NO. Thus ammonia addition to the exhaust stream may not be required.

Industrial Collaboration

As previously discussed Magnequench International, Incorporated has supplied two linear alternators at no cost in order to develop new applications for rare earth permanent magnets. In addition, Caterpillar Corporation is entering into an information-sharing agreement with our group. The purpose of the collaboration is for CAT to share their free piston lubrication and sealing technology with Sandia while in return applying our linear alternator technology to their free piston hydraulic pump program.

This year Unique Mobility Inc. has expressed interest in collaborating in this program. Their specialty is in the area of permanent magnet motors and power electronics. Both areas of expertise will be of great value to this program.

All three of these collaborations will ease the transfer of this exciting new technology to the industrial sector.

Future Work

Plans for the 2002 fiscal year include completing the two-stroke scavenging system design, developing a comprehensive system model, designing a prototype starting system and quantifying performance of both alternator designs. The principal objectives are to select a prototype scavenging system, obtain a predictive model of electrical and mechanical components, select a starting system, and collaborate with industrial partners in pursuing other funding.

References

Achten, P. A. J. 1994. “A Review of Free Piston Engine Concepts,” SAE Paper 941776.

Alperstein, M., Swim, W. B. and Schweitzer, P. H. 1958. “Fumigation Kills Smoke – Improves Diesel Performance,” SAE Transactions, vol. 66, pp.574 – 588.

Baruah, P. C. 1988. “A Free Piston Engine Hydraulic Pump for an Automotive Propulsion System,” SAE Paper 880658.

Braun, A. T. and Schweitzer, P. H. 1973. “The Braun Linear Engine,” SAE Paper 730185.

Caris, D. F. and Nelson, E. E. 1959. “A New Look at High Compression Engines,” SAE Transactions, vol. 67, pp. 112-124.

Christensen, M., Johansson, B. and Einewall, P. 1997. “Homogeneous Charge Compression Ignition (HCCI) Using Isooctane, Ethanol, and Natural Gas – A Comparison With Spark Ignition Operation,” SAE Paper 972874.

Christensen, M., Johansson, B., Amneus, P. and Mauss, F. 1998. “Supercharged Homogeneous Charge Compression Ignition,” SAE Paper 980787.

Das, L. M. 1990. “Hydrogen Engines: A View of the Past and a Look Into the Future,” International Journal of Hydrogen Energy, vol. 15, no. 6, pp. 425 – 443.

Edson, M. H. 1964. “The Influence of Compression Ratio and Dissociation on Ideal Otto Cycle Engine Thermal Efficiency,’Digital Calculations of Engine Cycles, SAE Prog. in Technology, vol. 7, pp. 49-64.

Karim, G.A. and Watson, H.C. 1971. “Experimental and Computational Considerations of the Compression Ignition of Homogeneous Fuel-Oxidant Mixtures,” SAE Paper 710133.

Klotsch, P. 1959. “Ford Free-Piston Engine Development,” SAE Paper 590045.

Lee, W. and Schaefer, H. J. 1983. “Analysis of Local Pressures, Surface Temperatures and Engine Damages under Knock Conditions,” SAE Transactions, vol. 92, section 2, pp. 511 – 523.

Maly, R. R., Klein, R., Peters, N. and Konig, G. 1990. “Theoretical and Experimental Investigation of Knock Induced Surface Destruction,” SAE Transactions, vol. 99, section 3, pp. 99 – 137.

Muranaka, Y. T. and Ishida, T. 1987. “Factors Limiting the Improvement in Thermal Efficiency of S.I. Engine at Higher Compression Ratio,” SAE Transactions, vol. 96, section 4, pp. 526 – 536.

Najt, P. M. and Foster, D. E. 1983. “Compression – Ignited Homogeneous Charge Combustion,” SAE Paper 830264

Onishi, S., Jo, S. H., Shoda, K., Jo, P. D. and Kato, S. 1979. “Active Thermo– Atmospheric Combustion (ATAC) – A New Combustion Process for Internal Combustion Engines,” SAE Paper 790501.

Overington, M. T. and Thring, R. H. 1981. “Gasoline Engine Combustion – Turbulence and the Combustion Chamber,” SAE Paper 810017.

Thring, R. H. 1989. “Homogeneous-Charge Compression-Ignition Engines,” SAE Paper 892068.

Underwood, A. F. 1957. “The GMR 4-4 ‘Hyprex’ Engine – A Concept of the Free-Piston Engine for Automotive Use,” SAE Paper 570032.

Van Blarigan, P., and Green R. 1995. “NO_x Emission Data Verified in a Hydrogen Fueled Engine,” Combustion Research Facility News,” vol.17, no.4, January/February.

Williams, Robert. January 1996. “Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO_2,” PU/CEES Report No. 295.