Proceedings of the 2002 U.S. DOE Hydrogen Program Review
NREL/CP-610-32405

ADVANCED INTERNAL COMBUSTION ELECTRICAL GENERATOR

Peter Van Blarigan
Sandia National Laboratories
Livermore, CA 94550

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 (e.g. H_2, CH_4O, NH_3, Biogas, etc.). 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 and painlessly.

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 were in place then the additional cost of natural gas reformation and subsequent CO_2 sequestration would be minimal (Williams 1996). Decarbonization of fossil fuels with subsequent CO_2 sequestration to reduce or eliminate atmospheric emissions provides a transition strategy to a renewable, sustainable, carbonless society. However, this requires hydrogen as an energy carrier.

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 are 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 condition 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 IC 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 (ϕ) is no longer required to be precisely controlled, as is required in conventional stoichiometric operation when utilizing tree 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 (HCCI) combustion 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 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 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 CR=16.25:1. The results indicate 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.

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.

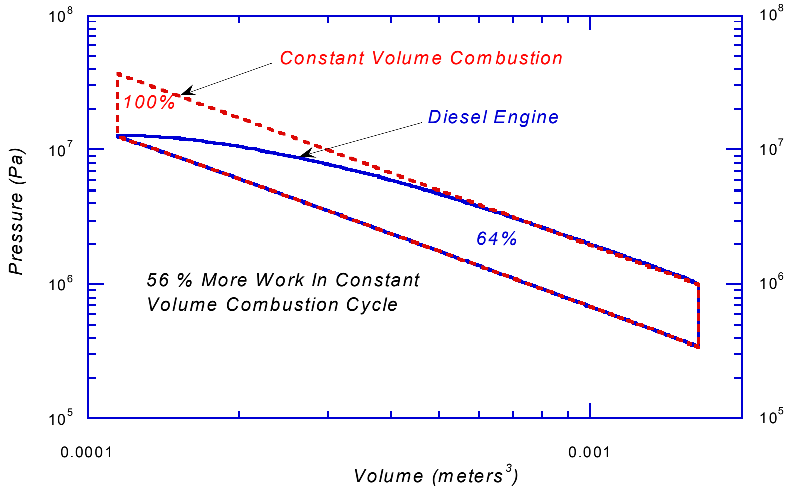

Figure 1 – Modern 4-Stroke Heavy Duty Diesel Engine

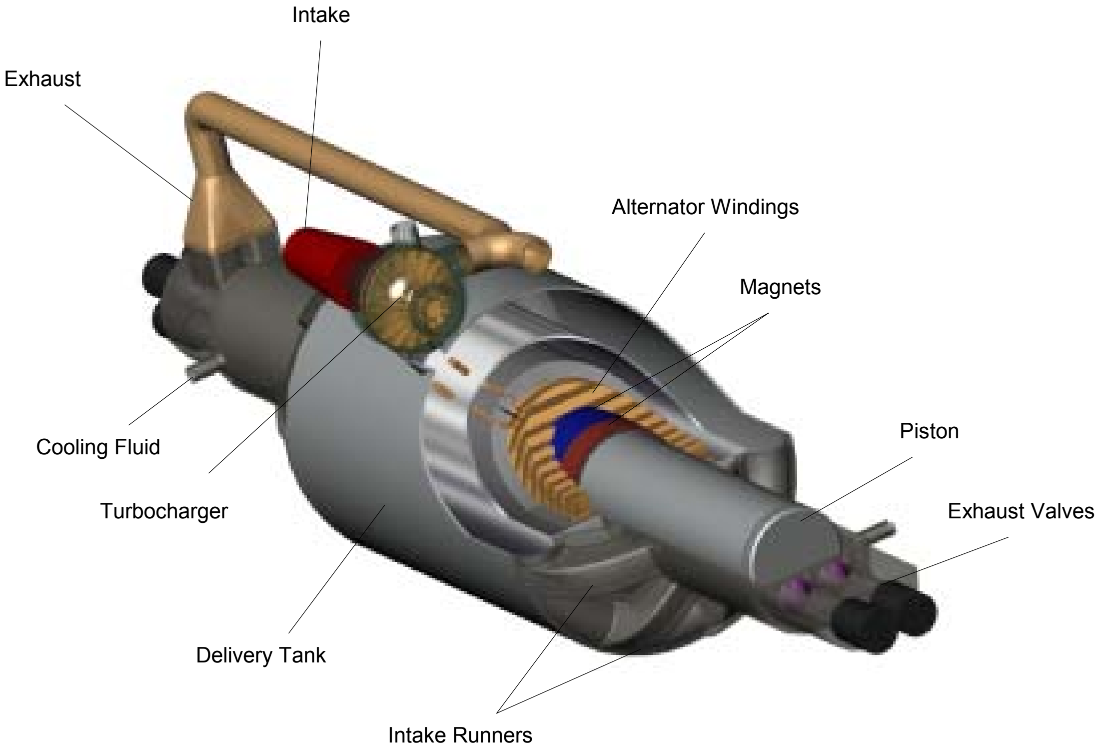

Figure 2 – Free Piston Linear Alternator

The linear alternator 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.

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 IMEP levels inherent in low equivalence ratio operation due to the reduction in mechanical friction.

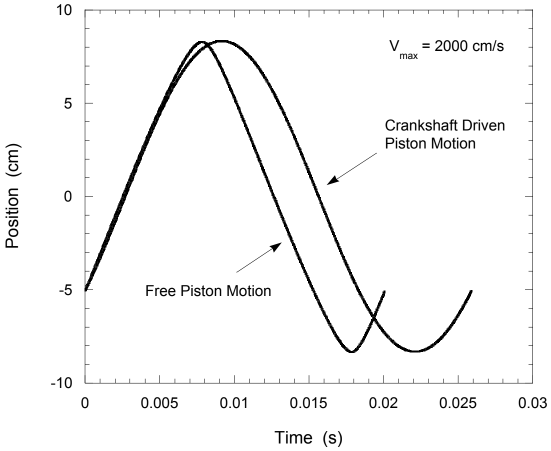

Figure 3 – Piston Position vs. Time

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. This class of motors is characterized by high efficiency and high power density, typically 96% efficiency and 1 hp per pound density. 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 since not all the coils are driven at the same time. Efficiency however, will be comparable.

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 two-stroke cycle engines have developed a reputation however 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 two-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 the Sandia design the requirements are quite different. The speed of the free piston oscillation is essentially fixed, and power is varied by decreasing the equivalence ratio, or by adding some level of boost. However, 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.

Combustion System Analysis

An experimental investigation of the free piston, HCCI combustion system was undertaken through FY2001. Some typical results are presented here to verify the soundness of the approach for this development program.

Figure 4 shows the result of one of the studies completed with hydrogen. In this investigation, a single-stroke rapid compression-expansion machine (RCEM) was used to compression ignite homogeneous fuel/air mixtures. Hydrogen is the fastest burning fuel of all the fuels tested. The high rate of combustion does approach constant volume combustion. 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. Additionally, operation at equivalence ratios less than 0.5 reduces the need to consider piston erosion, or other physical damage (Maly et al. 1990).

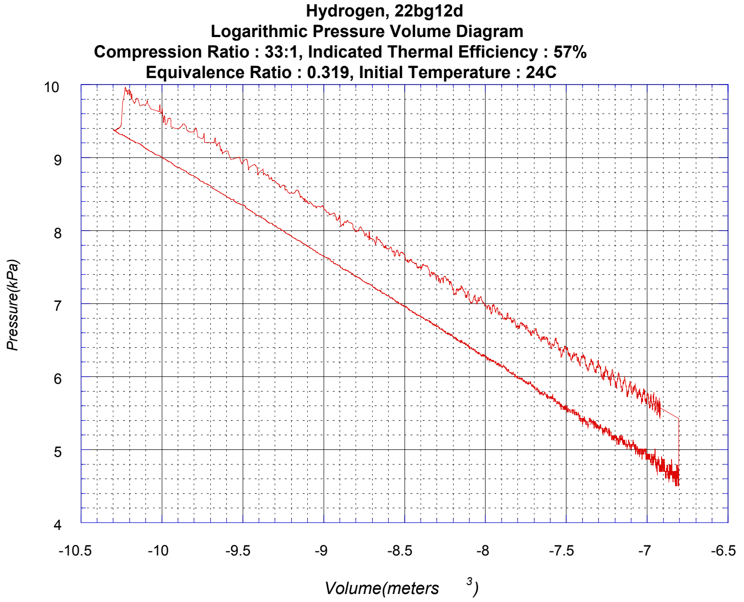

Figure 4 - Hydrogen HCCI Combustion using the RCEM

Results - FY 2002

The objectives of this program for the fiscal year 2002 were to continue to design, build, and test the advanced electrical generator components, and to develop industrial partnerships. The rationale behind the continuation of designing, building, and testing generator components was to produce a research prototype for demonstration in three years. Developing industrial partnerships will lead to the transfer of technology to the commercial sector as rapidly as possible.

Work conducted this year focused on the linear alternator, two-stroke cycle scavenging system, and HCCI combustion system. A description of this work is presented below.

Linear Alternator

Two parallel paths are being pursued to develop the linear alternator. First, an alternator is being designed, 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. The code, FLUX2D, is produced by MagSoft Corporation. We have investigated various design configurations, and have optimized a design with respect to maximizing efficiency and minimizing size. In parallel, Magnequench, a leading supplier of rare earth permanent magnets and a commercial development partner, has also designed and fabricated an alternator for this application. Both alternators will be tested under full design output conditions on a Caterpillar engine based tester. The Sandia-designed tester will measure both power output and mechanical to electrical conversion efficiency. A picture of the alternator tester is presented in Figure 5.

Figure 5 – Alternator Tester

The Sandia and Magnequench alternator designs are very similar; the differences are primarily in the coil configuration, magnet fabrication and stator material. The Sandia magnet assembly is fabricated from 10° arc magnet segments, which are magnetized in a linear direction. The stator is a stack of 1600 laminations punched from anisotropic oriented grain silicon steel. Each lamination has a small angle ground so the stack forms a cylinder. The coils contain 78 turns of square cross section wire.

The Magnequench magnet assembly is constructed of pressed neodymium-iron-boron rare earth material (to form a cylinder) and magnetized in the radial direction. The stator material is pressed iron powder in an adhesive matrix. The coils consist of a single row winding of flat wire. The Magnequench coils must be connected in moving groups of five as the magnet assembly moves during operation to generate sufficient voltage for efficient power conditioning. The Sandia design has sufficient voltage from a single coil and does not require coil switching.

Due to the difficulties encountered assembling the Sandia alternator the Magnequench design will be the first to be tested on our full power alternator tester. Three of the Magnequench units were received at Sandia as complete stator assemblies, but without the magnets or the magnet guide and support structure. Our first task was to design the mounting and support fixtures for a unit to be returned to Magnequench for their evaluation. The other two units are being configured for mounting on the Caterpillar engine based tester. The tester will oscillate the magnet assembly through a 15 cm stroke at 38 Hz.

The mounting features include a load cell suspension system for the stator. By measuring the actual loading on the stator, the mechanical work being applied to the stator can be calculated. The electrical power generated will be converted into heat in resistors, and the power generated will be calculated. With this information, mechanical to electrical efficiency can be determined.

The aluminum to steel inertial weld of the piston assembly was performed at Interface Welding in Los Angeles in early July. In parallel, sample welds of both the 7075 and 6061 aluminum to 1018 steel were evaluated by testing in tension to failure. The results of 7 full-scale pull tests reported failure levels between 270 to 310 kN for the 6061 aluminum samples. This level is consistent with the ultimate strength of the base material.

The 7075 samples were not as encouraging. During machining of the mounting features on the sample weld pieces, the welds failed and the samples fell apart. Careful examination of the interface revealed a clean break, appearing as if the parts had never been welded. Discussion of this problem with Interface Welding led to the suggestion of a short weld section of 6061 aluminum welded to the 7075 aluminum before welding to the 1018 steel. At this time we decided to not pursue this option and to proceed with 6061 aluminum parts. We will revisit this matter in the future.

When the welded piston assembly was received from Interface Welding in mid-July the part was sent to Production Robotics for final machining. At that time it was discovered that the part was not straight, wobbling approximately 1.5 mm in the center when supported at the ends. Production Robotics attempted to straighten the piece but broke their lathe trying. The part was returned to Sandia in early August, and an attempt to straighten the part was made on-site. The unit however, broke near the weld with no straightening accomplished.

More discussions with Interface Welding revealed that new tooling would be required to support the pieces more precisely during welding. This would require a greater tooling cost and more time. It was decided to try an alternative to inertial welding.

The current plan is to machine a one-piece aluminum piston from 7075 material and bond the steel back iron section to the aluminum in two clamshell halves. This will be slightly heavier than a welded assembly, but straightness is guaranteed by the process. This will at least allow the alternator to be tested, and we can revisit the inertial welded assembly when we are closer to a final prototype design.

Two Stroke-Cycle Scavenging System

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 multi-dimensional modeling to design the scavenging system and then to validate the computational predictions for selected operating conditions with the use of a single-cycle scavenging machine. Towards this goal we have used the computational fluid dynamics code KIVA-3V, developed by Los Alamos National Laboratory, to analyze various scavenging methods and configurations in an attempt to achieve an optimal arrangement. In addition, the scavenging machine is being designed and fabricated to verify the computational results.

Important goals to be achieved with the scavenging design are high scavenging efficiency (η_{sc}>90%) (replacement of the burned combustion gases with a fresh fuel and air mixture) and high trapping efficiency (η_{tr}>97%) (little loss of fresh charge through the exhaust ports/valves). High scavenging efficiency is desired in order to reduce the overall cylinder gas temperature at port/valve closure, and thus maximize the achievable compression ratio for the HCCI combustion process, since more compression will be required to initiate autoignition. High trapping efficiency is required in order to maintain the overall thermal efficiency of the engine, and to minimize the engine's unburned hydrocarbon emissions, when fueled on hydrocarbon fuels. Other goals important to the gas transfer design are adequate charge homogeneity at the time of combustion, ease of fuel introduction, mechanical simplicity, and low pumping power.

For the computational study loop, inverted-loop and uniflow scavenging methods were investigated, as well as options for the intake charge compressor. In addition, operating schemes including a low charging pressure option, a stratified scavenging geometry, and an over-expansion (Atkinson) cycle have been studied. Some of the results from these analyses are presented below.

A loop-scavenged option was investigated first due to its potential for a mechanically simple system. Parameters studied include intake charge pressure, port placement and lead angles (2 intake, 1 exhaust), and reciprocating speed. The KIVA simulations indicated that the fresh charge generates a helical-type motion within the cylinder and this motion aids in the preparation of a uniform charge for TDC HCCI combustion. However, the mixing dynamics encourages fuel short-circuiting through the exhaust port. Significant trapping losses (η_{tr}~0.7) ensue for sufficiently high scavenged operation (η_{sc}~0.8); this is especially complicated by the relatively high 2:1 compression stroke to bore ratio used (for adequate clearance at TDC). Additionally, for the configurations considered either high pumping losses, or low power output must be sacrificed 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. The goal was to generate fluid motion which would sweep the exhaust gases up along the wall of the cylinder (in a swirling fashion) and then down the center toward the burned charge at the bottom of the cylinder. Parameters studied include the intake/exhaust port arrangement, intake charge pressure, and reciprocating speed. The KIVA simulations indicated that pressure fluctuations within the intake manifold due to the intense blowdown, and flow oscillations across the exhaust port dramatically affect the in-cylinder flow and that the desired swirling-loop cannot be achieved. As such, 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% removal of the exhaust gases 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 6. This configuration also allows variation of the exhaust timing to create various degrees of over-expansion since the valves are controlled independently of the piston position.

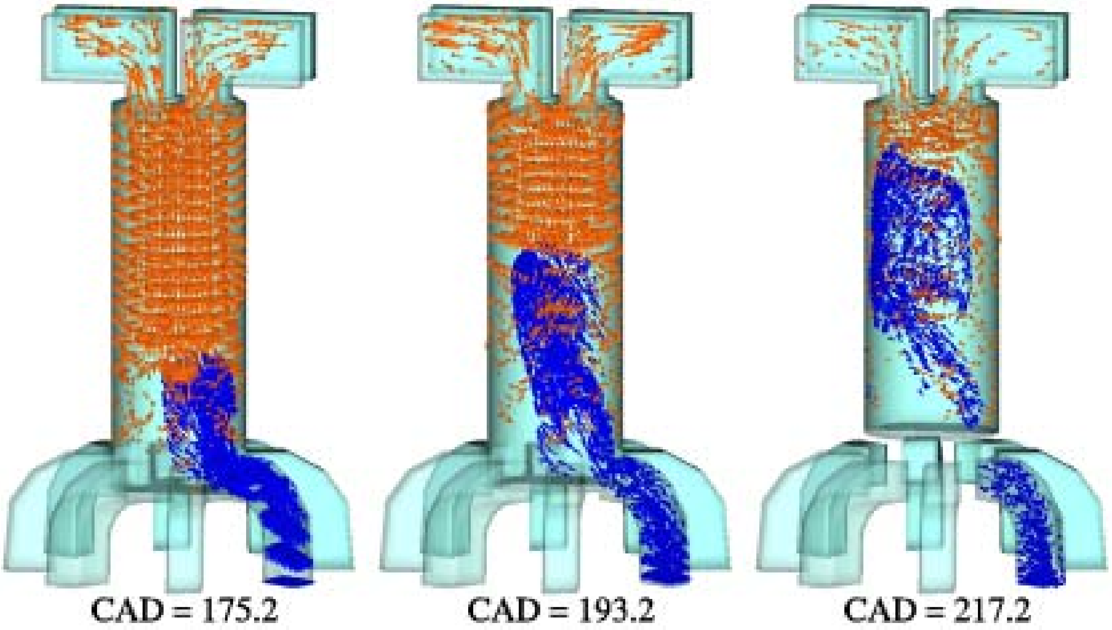

Figure 6 – KIVA-3V Calculated Uniflow Scavenging

A zero-dimensional (0D) model was used to analyze options for the charge delivery system. The delivery system was assumed to include a stepped-piston compressor (integrated into the alternator component) and a delivery tank. This provided a reasonable means of determining how the intake charge compression process affects the cycle performance, in terms of efficiency and scavenging capability. The charge delivery analysis was undertaken with the goal of minimizing the pumping work while maximizing the scavenging and trapping efficiencies.

Parameters that were varied include the compressor compression ratio, the tank volume, valve flow area, and tank temperature. These 0D and coupled KIVA-3V simulations indicated that a large tank (to stabilize the delivery pressure), maximum inlet/outlet flow area, and a cooled tank (to reduce the temperature of the trapped cylinder charge) will maximize the scavenging performance, while at the same time increase the overall thermal efficiency of the engine.

The final computational analysis for the scavenging system investigated four different operating schemes. These were: a nominal arrangement with 8 intake ports and 4 vertical valves using a charging pressure of 1.2 bar and a moderate operating frequency of 45 Hz; a very low charging pressure (1.1bar) / low frequency (33Hz) arrangement; a stratified scavenging configuration where a fuel rich mixture is introduced late in the scavenging cycle to increase the scavenging efficiency while at the same time limiting fuel short-circuiting (4 tall air ports and 4 short fuel/air ports); and a configuration to allow over-expansion of the cylinder charge (Atkinson cycle). These geometries were constructed so that similar power production could be achieved - the volume was increased for the low frequency option, while it was decreased for the stratified scavenging option (since the trapped cylinder charge has a lower density). As well, the valve and port timing/areas were adjusted to achieve reasonable scavenging efficiencies (0.83 for the nominal, low pressure, and over-expansion options; 0.93 for the stratified option) with low trapping losses (<1-2%). An effective equivalence ratio (accounting for dilution with residual gases) of 0.38 was used. For these variations a 1D friction model was employed to determine how the changes in scavenging configuration affect the friction losses.

Computations were made to determine the effect of the operating scheme on the overall cycle thermal efficiency (including combustion cycle, pumping work and friction losses) and output emissions, defined as NOx and short-circuited fuel. (The KIVA-3V calculations were not sophisticated enough to determine partially-burned hydrocarbon emissions, so these were not considered. However, high NOx emissions indicated fuel rich regions during combustion and therefore these were evaluated.)

The results of these simulations indicated the following:

1. The reduction in charging pressure is offset by the increase in delivered mass (for similar output power), and this results in similar pumping power consumption. The lower piston speed is offset by the increase in cylinder bore and ring diameter, and therefore the friction work is similar. The efficiency and emissions results are identical to the nominal power case.
2. The stratified scavenging configuration significantly improves the indicated efficiency of the cycle by increasing the operating compression ratio (24:1, compared to 17:1). The pumping power increases slightly, since the flushing process requires more charge flow through the cylinder. Overall, the brake efficiency is improved (+10%) relative to the nominal case. On the other hand, the short-circuited fuel emissions are significantly higher since only small amounts of escaped fuel-rich gas can dramatically alter the unburned fuel emissions. The NOx levels are similar to the nominal configuration, indicating similar mixing during the compression process.
3. The over-expanded configuration improves the indicated efficiency, though not as much as the stratified scavenging case, since more work can be recovered from the combustion gases before the scavenging process starts. However, friction losses are substantially more because the piston stroke is significantly increased (2X) to account for the additional expansion. To achieve the same operating frequency the mean piston speed increases. Overall, the brake efficiency is only slightly improved (+5%). The NOx and unburned fuel emissions are similar to the nominal configuration.

Additional investigations were conducted with these four operating schemes to determine the ‘robustness’ of each design. For these studies small variations (±10%) in intake equivalence ratio and operating frequency were simulated. Two conclusions were drawn from these computations. First, the nominal and stratified scavenging configurations both result in large unburned fuel emissions for small decreases in piston frequency. This is due to the additional time available for short-circuiting. Second, the over-expanded scheme is (at least computationally) unstable, as small changes in the operating conditions cause large cycle-to-cycle variations in charging efficiency and power output.

NASA Study

This past summer NASA-Langley requested assistance from Sandia to determine the feasibility of Free Piston Electrical Generators in providing the propulsive power for aircraft. The concept is to distribute generators throughout the aircraft and utilize electric motor powered fans to propel the plane.

The study is useful to the Hydrogen Program because it allows our investigation of operating parameters to be broadened to include improvements not previously considered, while these studies are costed to other programs.

One discovery made during this study is 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 is 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 4 kW of output power.

The key area of investigation was to determine if high fuel conversion efficiencies (56% seen previously) could be maintained at a 2 kW size. Problems anticipated related to the greatly increased surface to volume area of the combustion chamber at ignition, and the reduced time available for combustion due to the higher oscillation rate (six times faster). On the other hand, if the combustion event is fast enough then the increased oscillation rate will reduce the time for heat loss, compensating for the larger surface to volume ratio. An experimental investigation is the best approach to answering these questions.

A small rapid compression expansion machine was fabricated with a bore of 1.2 cm, compared to the larger RCEM dimension of 7.6 centimeters, and is shown in Figure 7.

After typical experimental problems were resolved we were able to measure efficiencies comparable to the larger apparatus. Figure 8 shows the near Otto cycle performance achieved, which is similar to Figure 4. To accomplish these operating results however, it was necessary to increase the equivalence ratio by a factor of almost two. This may lead to NOx emissions problems, but we have not been able to measure these with the small quantity of gas produced. The intended applications for a generator of this size, though, do not consider NOx emissions as a primary design goal. As such this may not be a significant issue.

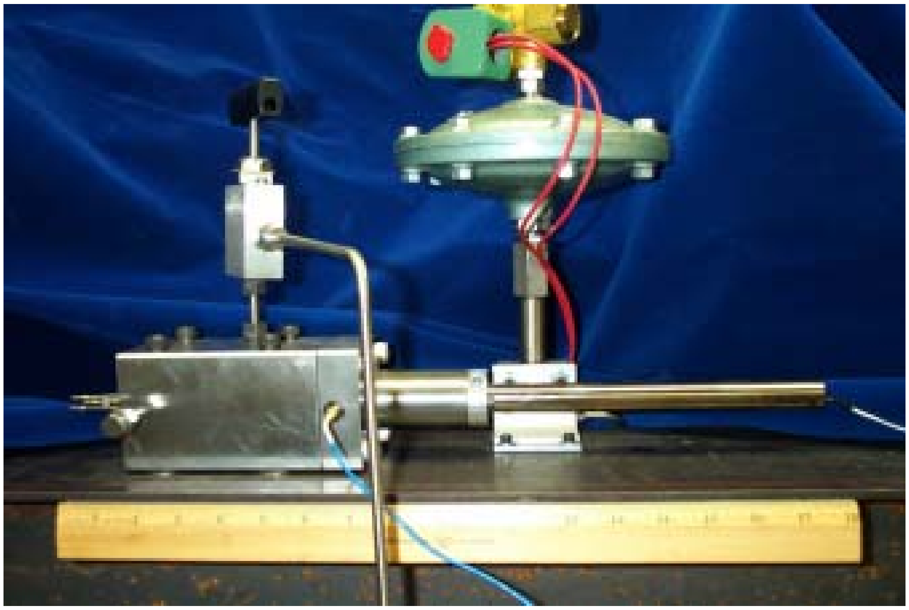

Figure 7 – Small Rapid Compression Expansion Machine

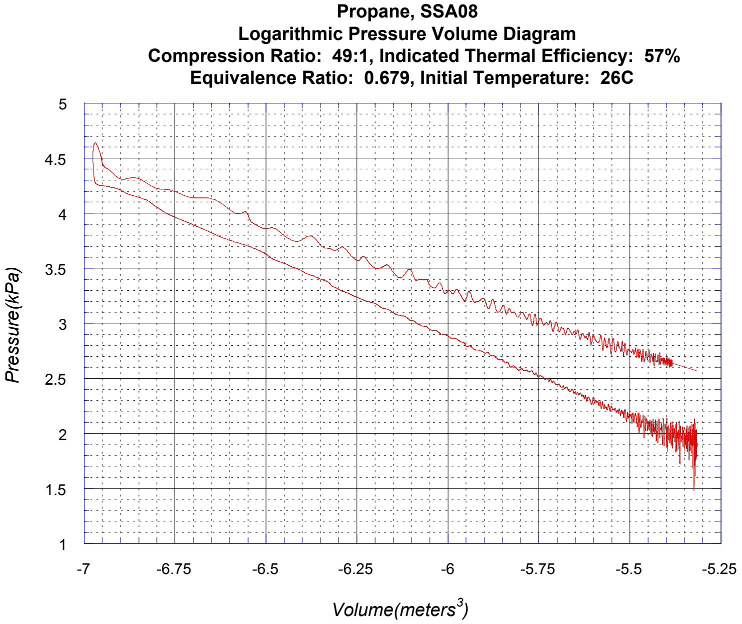

Figure 8 – Propane HCCI Combustion using the Small RCEM

Industrial Collaboration

As previously discussed Magnequench International, Incorporated has supplied linear alternators at no cost in order to develop new applications for rare earth permanent magnets. In addition, 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.

These collaborations are expected to ease the transfer of this exciting new technology to the industrial sector.

Future Work

Plans for the 2003 fiscal year include completing the scavenging experiment design and constructing it, developing a comprehensive system model, designing a prototype starting system and quantifying performance of both alternator designs. The principal objectives are to develop a prototype scavenging system, obtain a predictive model of electrical and mechanical components, configure a starting system, and collaborate with industrial partners to pursue other funding and commercialization of the engine generator.

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., Paradiso, N., and Goldsborough, S. 1998. “Homogeneous Charge Compression Ignition with a Free Piston: A New Approach to Ideal Otto Cycle Performance.” SAE Paper 982484.

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.