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Final Progress Report (sent via Email)

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Report Title: "Portable Power Generation Based on Mesoscale Free-Piston Knock Engine"

Is forwarded for your information.

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13. ABSTRACT (Maximum 200 words)

The objective of this program is to develop and demonstrate a mesoscale free-piston knock engine operating on a variety of hydrocarbon fuels, such as propane, ethane, butane, and diesel. The goal is to deliver a 500 W pneumatic output in a 200 cm3 packaged volume, which can be used to power various mechanical systems, or to generate electricity via a high-speed air motor and generator. The overall engine efficiency goal is 44%, thus giving a hydrocarbon-based power source an energy density of 5500 Wh/kg.

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Enclosure 1

Portable Power Generation Based on Mesoscale Free-Piston Knock Engine

Contract No. DAAD19-01-C-0089

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Statement of the Problem Studied

The objective of this program is to develop and demonstrate a mesoscale free-piston knock engine operating on a variety of hydrocarbon fuels, such as propane, ethane, butane, and diesel. The goal is to deliver a 500 W pneumatic output in a 200 cm^3 packaged volume, which can be used to power various mechanical systems, or to generate electricity via a high-speed air motor and generator. The overall engine efficiency goal is 44%, thus giving a hydrocarbon-based power source an energy density of 5500 Wh/kg. Figure 1 illustrates the Mesoscale Free-piston Knock Engine concept

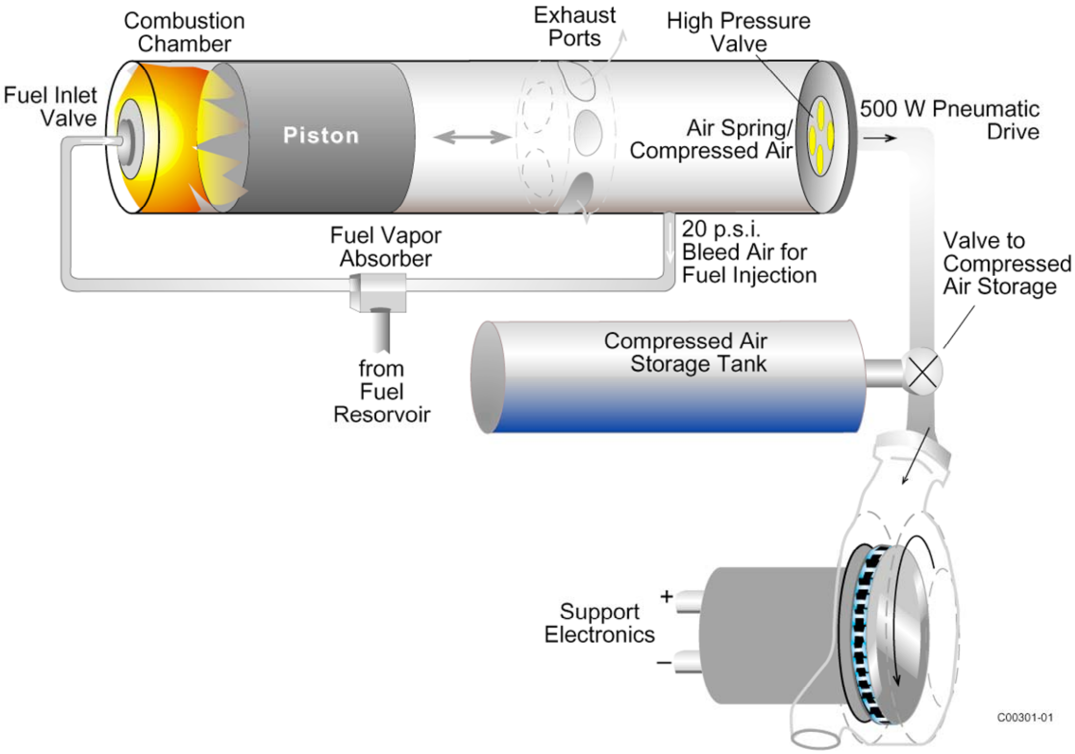

Figure 1 - Mesoscale Free-piston Knock Engine Concept

The program consists of a base plus option phase. The base program tasks are (1) Scaling Studies and Engine Design and, (2) Initial Ignition Experiments. The option program task is (3) Cylinder/Piston Fabrication. There is a program management task covering the complete program.

Summary of Most Important Results

Modeling Studies – Combustion thermal-mechanical computer modeling using ideal gas data has been performed. The model includes a heat transfer and combustion model that is calibrated by experimental data. Initial modeling results indicate favorable performance with the upper efficiency limit of about 70%. The technical approach applied in these modeling studies is shown in Figure 2.

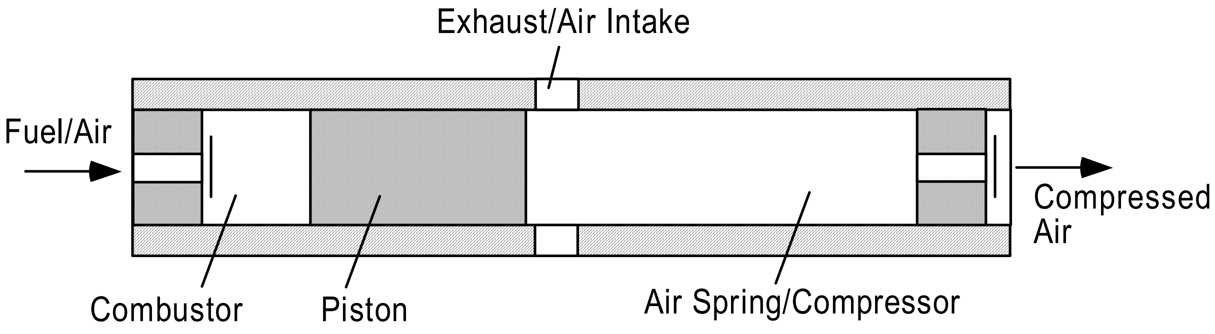

Figure 2 - Mesoscale Free-piston Knock Engine Technical Approach

Real gas data has been implemented into the model. Using the real gas data, the optimized efficiency is 64-68% not counting friction and leakage losses (Figure 3). The lowered value than using ideal gases is due to lower γ of the realistic exhaust gas containing large amount of CO_2. Another factor in the discrepancy between the modeling and experimental result is mainly due to leakage, which is evident in our compression energy balance measurement. In addition, the non-uniformity of the tube may have caused the airfoil failure in some sections thus increasing the friction significantly.

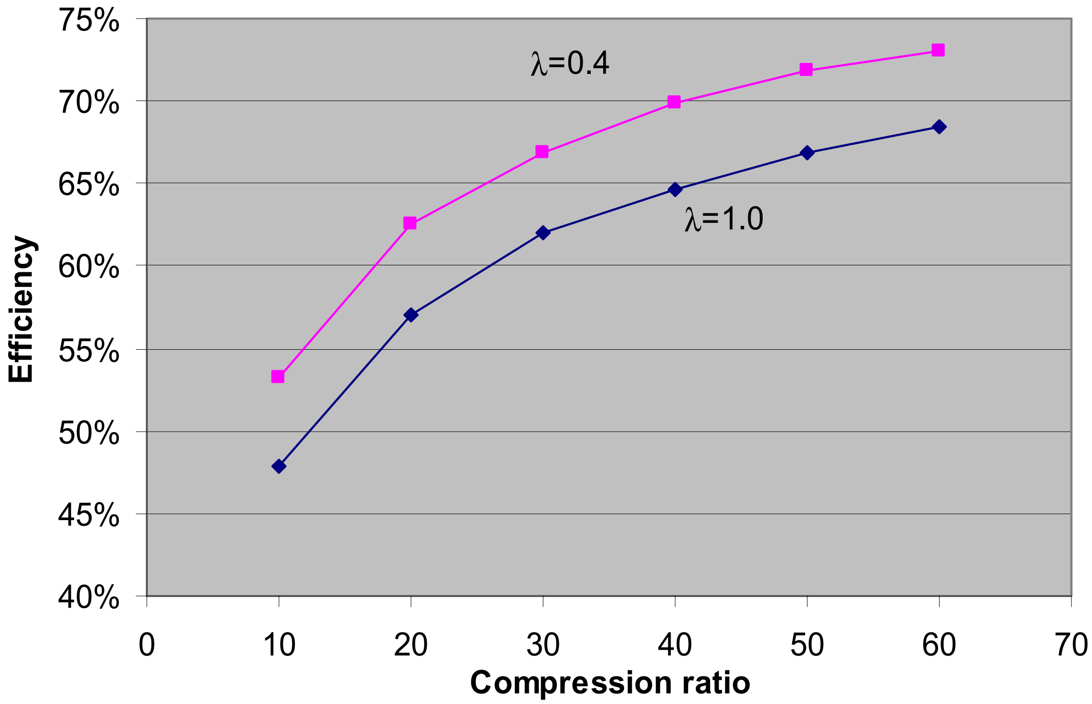

Figure 3 – Modeling of Thermal mechanical efficiency

Efficiency Measurements – Thermal mechanical efficiencies ranging from 15-35% have been measured in the 8 mm homogeneous charge compression ignition (HCCI) setup (Figure 4) with unoptimized fuel-air ratios. The efficiency is affected mainly by the piston mass. Typically a large piston mass leads to premature ignition at a compression ratio of around 20:1 and low efficiencies in the range of 10-20%.

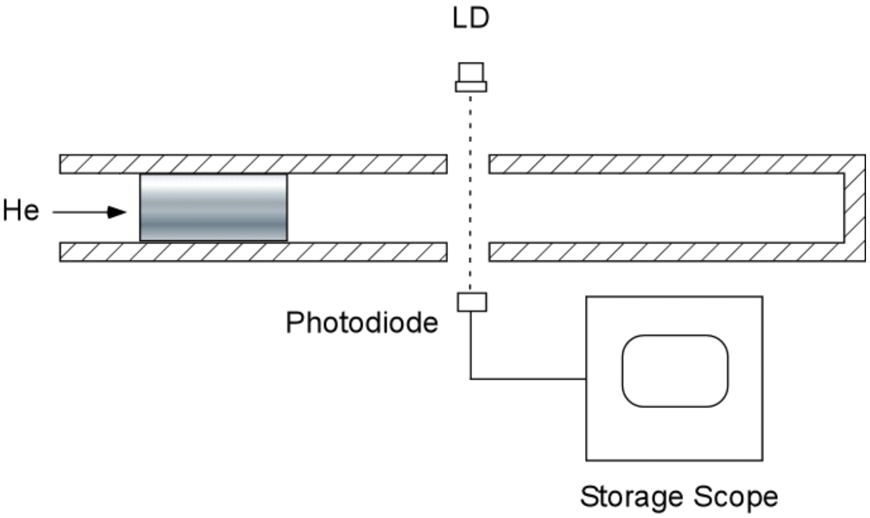

Figure 4 – HCCI Test Setup

The low efficiency is attributed to the higher heat losses due to the slower piston speed, consistent with thermal-mechanical modeling. Light pistons have given much better results, 30% or higher, and show a continued trend of increasing efficiency with smaller masses. The data on the small mass end is not yet complete due to drive speed limitations in our set up. An example of efficiency vs. piston speed is shown in Figure 5.

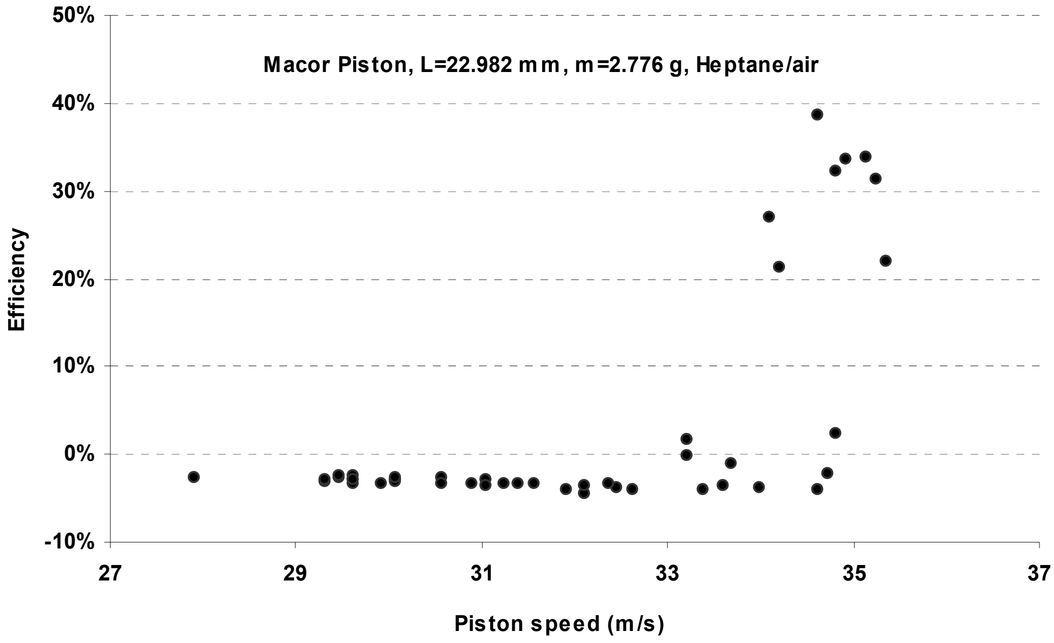

Figure 5 – Efficiency Data Using HCCI Test Setup

Cylinder Break-in Process – In the effort to improve the roundness and axial uniformity of the cylinder tubing, we have built an internal diameter (ID) grinding apparatus using pneumatically driven, reciprocating ceramic pistons. A set of high precision alumina and Macor pistons have been fabricated with graduated diameters. We used these pistons to enlarge the ID of the tube gradually, thus improving their roundness and axial uniformity. In the initial test runs, the grinding apparatus using the grinding pistons appears to be able to increase the inner diameter of the stainless steel tubing. Over 16 μm of material removal has been achieved in about one hour. We expect the grinding action to be homogeneous in both radial and axial directions, therefore in theory the tube should approach perfect roundness as the enlargement progresses. As the tube approaches perfect roundness and uniformity, the piston eventually glides on an airfoil and the grinding action self terminates.

The alumina pistons are well suited for the grinding purpose. They were produced by centerless grinding and have textured surfaces that allow filling of certain amount of metal. Once the surface is filled, the grinding capability decreases and jamming starts to occur. The piston can be “regenerated” by etching in aqua regia to remove the metal deposit. Since alumina is extremely stable, this process can be repeated many times. Two problems with the current setup have emerged. One is the stability of the pneumatic driver without any feedback control which results in drift of the piston towards one end and collision with the plug. Another problem is slight deformation of the stainless steel tubing incurred during the ports drilling, which frequently leads to jamming. This has been a major source of frustration. Using EDM to open the ports has reduced the problem but minor deformation is still evident. The solution appears to be using thicker wall tubes (the wall currently is about 1 mm).

Another approach is to push a tungsten carbide ball through a raw tube (ballizing). This is essentially a cold forming process and should produce nearly perfect circularity and uniformity. An additional benefit is the surface hardening during the forming. The deformation during ballizing is partially plastic, therefore the final ID is always smaller than the ball diameter. However, the tube ID can be controlled after a series of experiments. The major factors affecting the final ID include the wall thickness and the ball oversize. Tungsten carbide balls have been used in single or multiple steps in this process. First we ballized existing 316 stainless steel tubing which an electropolished ID surface. About 50 μm to 100 μm enlargement of outside diameter (OD) was achieved. Initial compression experiments with ballized tubes show significant reduction in leakage, even with non-optimal piston matches. Figure 6 illustrates the difference in surface finish between a reamed and ballized tube.

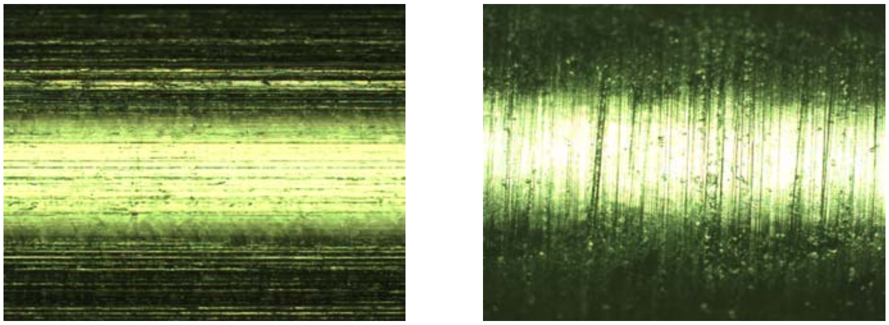

Figure 6 – Reamed vs. Ballized Cylinder Wall

Cylinder Selection – Three types of tubes have been used for the cylinder fabrication. The first type, thin-wall (~1mm) stainless steel tubes with 8mm ID, have been ballized with ports made by EDM. The ballizing was performed before and after the ports machining. One difficulty in handling these tubes is that they are very sensitive to external stress. Even a slight bump on a hard surface may cause deformation enough to jam the piston.

The second type of tube has been provided by a local company specializing in gun drilling. The tubes were machined from solid rods by drilling, reaming, and multiple honing processes. The tube inner surface was highly polished. However, the uniformity of the diameter is unsatisfactory. The tubes gave a larger leakage than the thin wall tubes in compression tests. We also ballized one of these tubes and hope to improve the uniformity. This did not seem to be effective and no improvement in the leakage test was seen. The ineffectiveness of ballizing may be attributed to the inhomogeneity of the steel. We also noticed significant galling of the inner surface, which suggests that a highly smooth surface is not desirable for ballizing.

A third type of tube was purchased from a tubing vender. These tubes have thicker walls and are about 8 mm ID. The inner surface is quite rough and a reaming was performed before ballizing was done. The ballizing following reaming produced a specular surface finish, helped by the rough machine marks left from reaming that run perpendicular to the direction of the ball movement.

A fourth type of cylinder tube was evaluated. We looked into the possibility of using ceramic tubing but did not pursue this approach.

We investigated many port fabrication techniques. So far EDM-created ports are the best but still with some evidence of minor deformation around the port area.

A precision ID micrometer was procured that allows us to perform quick evaluation on the tube ID. The micrometer has a specified accuracy of 2 µm. Calibrations of the meter with gage pins and other OD micrometer have been performed to make sure consistency.

Precision Piston Selection – We had great success using ceramic (Macor) pistons to obtain jam-free operation. Due to lower densities of the ceramic material (~2.5), lower piston mass can be obtained more easily. The initial results are based on Macor pistons machined by a lathe, which do not have the desired roundness and uniformity.

Recommended Future Research – More research is required in the cylinder selection task. A complete study of the four tube types, including reaming and ballizing, is necessary for final down-selection. The precision piston selection process had just been started when the program was re-planned. Additional research into the piston vs. tube selection (i.e. efficiency measurements) would be fruitful.

Publications and Reports

Below is a listing of all publications and technical reports supported under this contract.

(a) Papers published in peer-reviewed journals – None
(b) Papers published in non-peer-reviewed journals or in conference proceedings – None
(c) Papers presented at meetings, but not published in conference proceedings
    (1) Program Kickoff, Jul-01, Alexandria, VA
    (2) DARPA PI Meeting, Nov-01, Maui, Hawaii
(d) Manuscripts submitted, but not published – None
(e) Technical reports submitted to ARO
    (1) Monthly Program Progress Report, Sep-01
    (2) Monthly Program Progress Report, Oct-01
    (3) Monthly Program Progress Report, Nov-01
    (4) Monthly Program Progress Report, Dec-01
    (5) Monthly Program Progress Report, Jan-02
    (6) Monthly Program Progress Report, Feb-02
    (7) Monthly Program Progress Report, Mar-02
    (8) Interim Progress Report, Mar-02
    (9) Monthly Program Progress Report, Apr-02
    (10) Monthly Program Progress Report, May-02
    (11) Monthly Program Progress Report, Jun-02
    (12) Monthly Program Progress Report, Jul-02
    (13) Monthly Program Progress Report, Aug-02
    (14) Monthly Program Progress Report, Sep-02
    (15) Monthly Program Progress Report, Oct-02
    (16) Final Progress Report, Nov-02

Participating Scientific Personnel

Dr. Wei Yang

Report of Inventions

None