# DIGITAL INTERNAL COMBUSTION ENGINES

by

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**ABSTRACT**

The design of a piston engine operating entirely under cycle-by-cycle computer control and having no moving parts other than one power piston, one fluid charging piston and 3 integrated sleeve valves is described. The output power is electrical, pneumatic or hydraulic. The combustion process uses Homogenous Charge, Compression Ignition (HCCI) to achieve the best-known combustion method for reduction of offensive exhaust products. Piston travel entails no side loads or excessive friction from crank angularity thus allowing for very high compression ratios with attendant high efficiency. Piston and valve bearings have low inertial loading giving a high horsepower-to-weight ratio by operating at high speed. The engine design is well adapted to operating as the power plant in flight vehicles needing lightweight and high fuel efficiency. This hydraulic drive method obviates the need for gear reduction to either lifting rotors or wheels.

**BACKGROUND**

The internal combustion, piston engine has been known long enough for almost all possible variations on it to be tried, yet, there are combinations of its various components that are underexploited due to the overwhelming emphasis placed on shaft power output. This popular emphasis has overshadowed some basic and viable aspects of internal combustion engine design that are potentially useful in future products. This is especially true when the favorable economics of modern computer techniques are combined with the most desirable attributes of basic, piston-operated, internal combustion engines.

In the progression of events leading to future engines, it is commonly thought that a turbine-based device should be in the lead. This is distinctly not the case for power levels below about 100 horsepower. Both the fuel consumption and the horsepower-to-weight-ratio suffer using turbine designs due to the low efficiency of turbo compressors operating at low Reynolds numbers. This is a fundamental limitation of a turbine that is not experienced by piston machines as piston machines maintain the ability to efficiently compress air to very high pressure ratios down to horsepower levels of only a few watts thus maintaining their operating efficiency.

When the digital techniques of almost instantaneous computer control combine with certain aspects of an engine design that has essentially no inertial components, it is fair to call the resulting engine a *Digital Engine*. Such a piston engine will be described here whereby there is no flywheel, crankshaft or connecting rod incorporated in the design. All power is taken out by electric, pneumatic or hydraulic means from a straight piston stroke. Considering the plethora of engine designs suggested over the many years of developing modern engine technology, it would not be surprising if designs similar to the one proposed here had already been at least partially proposed by someone else. The design submitted here is a specific set of chosen variables to fulfill a particular need envisaged by the author. The designs are aimed primarily at airborne and portable devices whereby the need for efficiency and low weight are paramount. Additionally, it has been found that these specifications incidentally yield the lowest pollution per horsepower produced. Many such factors combine to indicate that this is an extremely fruitful design for several decades of use when all engine components are properly integrated with the overall device being devised.

At this point in the design work, the results of others have been the main guiding stimuli. In particular, the sleeve valve results of Sir Harry R. Ricardo have been incorporated as much as possible. Many of his engines were given wartime aircraft usage but many more of his best designs were only laboratory tested and never carried into production. In 1966 the author of this note used a version of a sleeve valve in a free-piston, gas generator engine design that was granted US Patent # 3,533,429 in 1970. The patent was entitled, “Pneumatically Operated Valve” and assigned to SRI International of Menlo Park, California where the author was employed as Staff Scientist. A drawing and a photo of this engine are shown in Fig. 1 and Fig. 2.

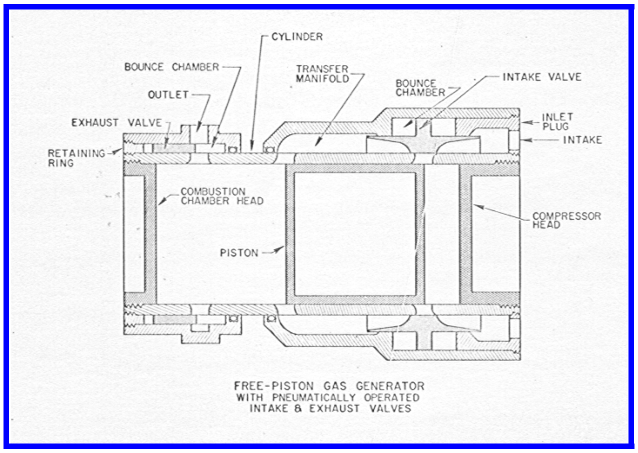


Fig. 1 Drawing of a free piston gas generator using pneumatically operated sleeve valves. Shown approximately actual size for 2 gas horsepower output. US Patent # 3,533,429 issued to K. R. Shoulders in 1970.

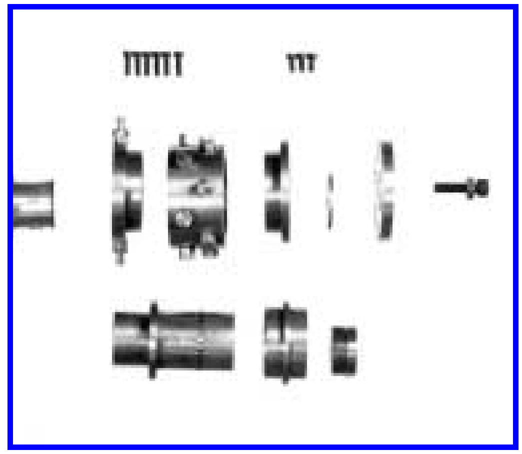

Fig. 2 Free piston gas generator components shown disassembled.

Since that time with SRI International, the author has reduced some of Ricardo's best designs to practice on a small size scale for laboratory testing. An example of one of these designs is shown in Fig. 3 and Fig. 4. In addition, components for these designs were fabricated from aluminum oxide ceramic for cylinder, sleeve valve and piston, as ceramics have exceptional properties for small engines. These components are shown in Fig. 5. Many years before this basic engine work, the author worked as an individual on a type of servo system using timed ignition of explosive gases to produce the motive output of the servo. This work resulted in experience with extremely high-speed valve operation that is incorporated into this new digital engine design.

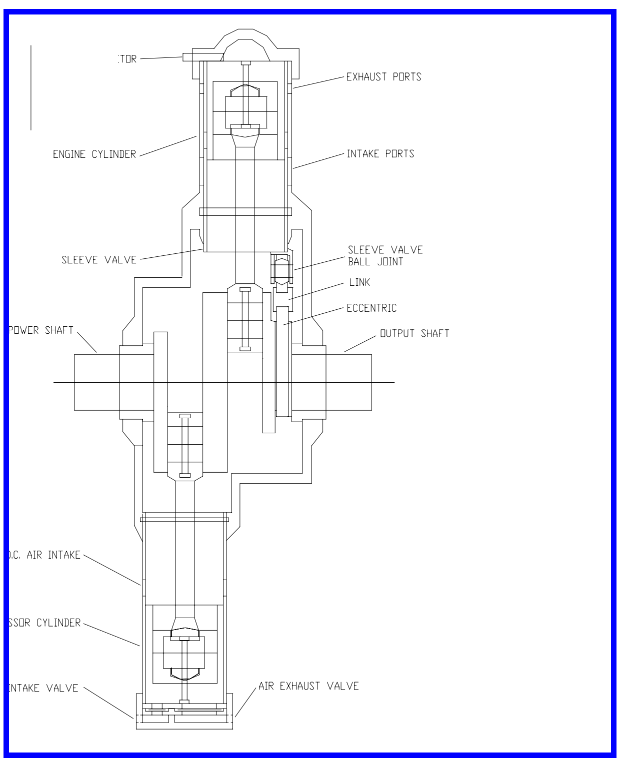


Fig. 3 Drawing of mechanically operated sleeve valve engine with 0.05 cu. in. displacement

As experience mounted and focus sharpened on applications having critical needs, it became clear that the design of power sources for most other applications had become stilted and unnatural thus causing a design warping toward shaft output power that, in turn, was causing great difficulties in some end-use devices. In particular, whenever a low speed output device like a helicopter rotor or automobile wheel is needed, the shaft power source greatly encumbers the overall design by introducing the need for a gear train. In other applications, such as heavy construction machinery, the auxiliary and control power need is high enough to easily justify a more direct hydraulic or pneumatic output.

The present digital engine design addresses the needs for a new generation of devices that integrate the power plant into the end use for a better overall design. This is seen particularly in a contra-rotating, propeller-driven, Vertical Take Off and Landing (VTOL) aircraft design presently being worked on by the author where the gearbox is the single most aggravating component. A hydraulic output engine coupled to a hydraulic drive for the lifting rotors appears as a blessed relief.

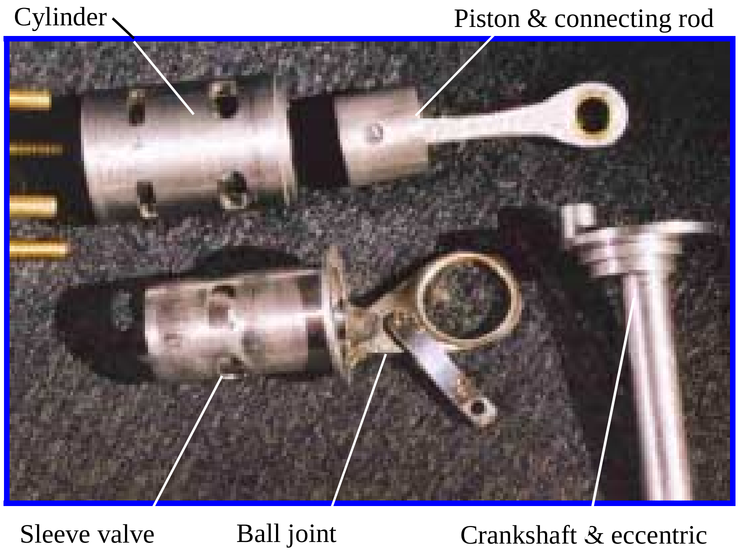


Fig. 4 Mechanically operated Sleeve valve engine components having 0.05 cu. in. displacement .

Fig. 5 Aluminum oxide ceramic cylinder, piston and sleeve valve for mechanically operated sleeve valve engine having 0.05 cu. in. displacement. Critical dimensions are fabricated to a tolerance of 5 micro inches.

Most heavy construction machinery has gone to this basic method but they still retain the rotary output from the engine coupled to a separate, rotary hydraulic pump. The design presented here circumvents dragging along the entrails of this historical method to produce better results for many of the weight sensitive applications to come.

As with all new designs or inventions, there is a risk of having too little basic knowledge to proceed quickly. This is certainly true of the new valve designs needed here as the most poignant properties of the engine depend on having good valving for working fluids. The main missing ingredient is specific data on the efficiency of high-speed valves. Although many high-speed sleeve valves have been made and tested by the author in the past, each variation was relatively painful and time consuming to build as the methods used were too cut-and-try. Any further work done in this area will first build up experimental background data concerning valve operating speed and damping, valve flow coefficients and thermal effects. This is largely an experimental effort involving fabrication of ceramic cylinders with appropriate valve openings cut in them and then testing the assembled parts of the valve. To properly perform this testing, a series of specialized devices like low volume pressure transducers and piston position indicators are needed and must be made. Successful completion of this part of the program will lead to a rapid final design of the engine proper.

## ENGINE DESIGN PHILOSOPHY

Before entering into a more detailed technical discussion of digital engines, it is advisable to cover some subjects broadly through philosophical renderings because when departing from conventional, shaft output engine design as far as this digital engine has, one enters into the realm of design philosophy instead of working with hard engineering facts. Consequently, a comparison will be drawn here between some of the known limitations of conventional engines and a proposed digital engine in an attempt to highlight the advantages of the latter. As with any such broad and shallow comparison, many opportunities for perceived errors are present and some errors will appear arising from such brevity.

One of the first points worth addressing is the viability of having a hydraulic output instead of shaft power. As alluded to earlier in this writing, end products needing high output torque from a small and lightweight engine operating at high speed, such as helicopter-like lifting rotors or traction wheels, can profit greatly due to the inherent torque conversion action of a hydraulic drive in the form of a piston motor. Such motors are efficient, versatile, lightweight and low cost when properly applied. Rotary hydraulic motors have a good history of performance but they are not very efficient. Even though this engine type prefers hydraulic output, it is also capable of directly producing nearly any combination of hydraulic, pneumatic or electrical output due to the high-speed piston oscillations.

Insofar as the basic mechanics go, this engine can be considered an analog of a free-piston engine without resonance and mechanical synchronization problems. Multiple cylinders can be employed in an effort to optimize heat transfer and minimize total failure due to failure of a single cylinder. All power output from the cylinders is accumulated in a hydraulic reservoir that is the energy storage mechanism for future cycles.

High compression ratios operating at high piston speed can be used in digital engines because the straight piston strokes without side loading from crankshaft angularity cause no compromise through lowered mechanical efficiency. In addition, the sleeve valves used have an enormous advantage over poppet valves because the clearance volume is vanishing small making all of the air accessible for combustion and expansion. The sleeve valve also provides for unidirectional flow of the working fluid leading to very good scavenging of the spent charge each cycle.

Although compression ignition is used during most of the operating cycles, there is an occasional need for spark ignition to recover from failed firings due to transient failure of fuel-air mixture. This is particularly true when operating at very lean mixtures.

The design proposed here is normally aspirated and not supercharged as this class of engine cannot profit by supercharging since the thermal limit of the engine can be reached by increasing its speed, something a shaft output engine cannot do due to large inertial loads on its bearings. Of course, there is a speed limit set by the hydraulic loss that has been traded for bearing loss. The main thrust of the work proposed here is to minimize this hydraulic loss through improved valve design and more will be said about that later.

One very unconventional aspect of the digital engine is its inherent ability to start or stop in a single cycle with no inertial carryover other than hydraulic surges. It is thus possible to modulate the power output from the engine by gating the various cylinders on and off under computer control without compromising the fuel efficiency. This natural starting ease is seen as a weight and cost advantage over using conventional engine starting methods.

The most desirable know combustion method for both fuel economy and reduction of pollutants that is described in the literature is <u>H</u>omogenous <u>C</u>harge, <u>C</u>ompression <u>I</u>gnition or HCCI. As the name implies, the fuel is intimately combined with the air and heated through high compression thus igniting the mixture. In almost all cases, the mixture is on the lean side of the stoichiometrically correct value. Under these conditions this combustion process is not stable in conventional shaft output engines and much work is still needed to accommodate its full potential using them. On the other hand, digital engine designs easily accept this method and there is no pre-ignition due to the many flame nucleation sites created. Even with lean charges, wild ping or detonation is not likely to occur at high pressure ratios because there is no end gas or peroxides to detonate at the high piston speeds used.

For these advantages of HCCI to accrete to the digital engine, it is necessary to properly meter and thoroughly mix the fuel and air while injecting them into the combustion chamber. Doing this increases the complexity of the engine over that of simple carburetion but it cannot be avoided.

Although high compression ratio engines can use almost any known fuel that can be injected, the fuel of interest here is likely to be gaseous at the time of injection even if it has to be heated first. This is done to improve mixing with air. One of the promising lines of fuel investigation is to use the hydraulic fluid as the fuel. Propane is a good candidate for both uses. If the fuel used is also the hydraulic fluid, it is necessary to use a low viscosity fluid like ethyl ether, alcohol, acetone, butane or pentane in order to avoid hydraulic losses.

The limiting speed of the digital engine is certainly to be set by the limits of efficient hydraulic flow through the valves controlling it and it is the aim of the work proposed here to push back this limit to a useful endpoint. Hopefully, this limit coincides with the thermal limit of the machine in an optimized design because the thermal limit is the ultimate limitation that cannot be easily circumvented.

Heat liberated in the combustion chamber is most desirably transferred to the load as mechanical power with as little as possible going to the exhaust gas due to the high compression ratio. Still, a significant amount of heat will pass through the cylinder, sleeve valve and piston wall setting the ultimate limit of dissipation. Ceramic materials are good for these components but they still have many problems due to non-uniform thermal expansion and increased friction at increased temperature. Also, the low heat conductivity of normal ceramics ultimately defeats external cooling but some of this heat can be alleviated by using cooled hydraulic fluid as a heat exchanger. A good selection for a thermally conductive construction material is beryllium oxide or silicon carbide but these are difficult to fabricate even though only simple cylindrical shapes are used.