Regenerative Internal Combustion Engine Part II: Practical Configurations

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The regenerative internal combustion engine cycles can be carried out in a series of mechanical configurations pertaining to two main families: bowl piston and flat piston. For each class, four-stroke and two-stroke types are presented. The peculiarities, advantages, and problems anticipated for each design are discussed. Possible problems are addressed, particularly those concerning emissions and speed limitations. Areas for further theoretical treatment and experimental research are pointed out.

General Design Criteria

THE requirements involved in the design of a regenerative internal combustion engine consist of the following:

1) The heat regenerated is to be taken from the exhaust gases as they leave the cylinder.

2) To be effective, this heat must be added to the compressed mixture at the end of the compression stroke, before combustion occurs.

3) The heat regenerated must be isolated from the cylinder during the rest of the cycle.

The main design criteria consist of the following:

1) No valve would withstand the high temperature of the combustion products. No valves should exist between the "hot" side of the regenerator and the combustion (and expansion) chamber.

2) The fresh gases should not come in contact with the "hot" side of the regenerator until the end of the compression stroke, to prevent early ignition. Physical separation is necessary.

3) Means have to be provided to generate a "sweeping" motion of all the compressed gas through the regenerator and into the combustion chamber at the end of the compression stroke.

4) In single-cylinder configurations, the compression and combustion occur in the same cylinder. A physical separation must also exist between the combustion chamber and the volume displaced by the power piston. This separation will be provided most effectively by a free piston moving within the cylinder.

5) The flows through the regenerator before combustion and after expansion must occur in opposite directions. Therefore, special means will be provided so that the "cold" and "hot" sides of the regenerator are switched to the appropriate ports at the right times.

With all of these criteria in mind, several designs are presented here for different cycles. They can be classified according to the cycle embodied (Table 1) or according to the main features of their physical configuration (Table 2).

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Bowl-Piston Engines

Four-Stroke Engine

Figure 1 represents the schematic configuration of a standard four-stroke regenerative engine. Notice the free piston inside the cylinder, above the power piston. This free piston must be very lightweight, since its motion is due to pressure forces on its two sides, during critical parts of the cycle.[1] The free piston will usually consist of a metallic laminated disk of corrugated construction, preferably with a rim around it, to prevent it from flipping inside the cylinder. The mission of the free piston is to isolate the combustion chamber below it from the compression space above it during the compression phase. A spark plug is used to ignite the fuel when the engine is started and the regenerator is still cold.

The regenerator is a piece of porous material that is capable of storing and releasing heat as the gases flow through it. In order to achieve a high effectiveness, it should have a sufficiently large internal surface area. This can be achieved by a packed matrix of very fine wire mesh or of randomly oriented ceramic fibers, or a spongelike metallic matrix. In order to prevent a large pressure drop when the gases flow through the regenerator,[1] it is convenient to make it rather flat, so that the flow cross section is as large as possible. This problem will not be as serious as in gas turbine applications (where the regenerator is usually larger than the rest of the engine) because the cycle pressures and temperatures are larger than in gas turbines, and the flow losses will not take a major fraction of the power. It is estimated that the regenerator will have a size comparable to that of the cylinder itself in most of the cases presented here, as is typical in Stirling engines.[2] In Figs. 1-14, the regenerator has been represented smaller than in reality to simplify the drawings.

The sequence of events of the four-stroke cycle in this configuration is represented in Fig. 2. Intake and compression are like those in a conventional engine, with the combustion chamber being separated from the compression by the free piston. Near the top of the stroke, a port is uncovered on the side of the piston, and the compressed mixture is pushed through the regenerator and this side port, into the combustion chamber. After top dead center (TDC), all of the mixture has been pushed out of the compression space, and the piston is held in place by the combustion pressure. During the exhaust, the gases are pushed out in the opposite direction through the regenerator, where they leave a part of their thermal energy. During part of the cycle, the free piston remains stationary, held by the strong combustion pressure acting on one side. During the rest of the cycle, it follows the motion of the power piston. The power piston will push the free piston in the up-

Table 1 Classification of regenerative engines according to cycle

Cycle	Four-stroke	Two-stroke
Otto	Three types	Two types
Diesel	Divided-chamber	—
Atmospheric	—	Atmospheric

Table 2 Classification of regenerative engines according to configuration

Configuration	Four-stroke Otto	Two-stroke Otto	Other
Bowl-piston	√	√	Atmospheric
Flat-piston	√	√	Two-piston
Divided-chamber	—	—	Diesel cycle

ward strokes, but in the downward strokes the direct solid contact between the power and free pistons may be lost. It will be necessary to guarantee a pressure force strong enough to maintain the contact. In this case, the intake stroke will be a problem, since the free piston must follow the power piston under the action of only the atmospheric pressure on one side and a partial vacuum on the other.

The combustion chamber in the piston is not likely to have large heat losses, but may force the adoption of ceramic insulation for the bowl region. The piston will be heavier than is usual in a spark ignition engine, although still lighter than that of a diesel engine.

Two-Stroke Engine

Figure 3 represents the two-stroke variation of the bowl-piston engine. Precompression is achieved under the piston or in an auxiliary compressor. The transfer channel runs all the way up to the cylinder head and is closed by a one-way flapper valve. This valve will be protected from the high pressure and temperature of the combustion gases by the free piston, which covers it during the expansion stroke. The regenerator is mounted on the piston, between the bowl space and the cylinder wall. The regenerator will normally be shaped as a drum on top of the cylinder, totally encircling the bowl. Figure 4 schematically represents the motion of the different elements during the cycle. Like in the four-stroke engine, regeneration is achieved by the opening of a transfer port near TDC. During the scavenging phase, the fresh mixture pushes the free piston across the cylinder, in turn pushing the exhaust gases out, through the regenerator. There is no contact between intake and exhaust gases, so that hydrocarbon emissions by fuel bypass are avoided. This configuration will be a little less limited by speed than the four-stroke type. Still, a high precompression will be necessary to move the free piston across the cylinder in the little time available for scavenging. Unless the precompression pressure is increased with engine speed, above a certain speed the free piston will not be able to cause a complete scavenge.

Atmospheric Engine

An atmospheric engine is that in which there is no compression stroke. The typical configuration of a regenerative atmospheric engine has been represented in Fig. 5. The sequence of events of this engine is represented in Fig. 6. After the new charge has flushed out the residual exhaust and filled the space above the free piston, the power piston reaches its top position, pushing the fresh mixture through the regenerator, into the bowl. Combustion and expansion follow. During most of the return stroke, the exhaust gases are pushed out through the regenerator. The free piston is held by springs to prevent it from moving beyond the regenerator lower port. The mixture fed to the engine must be precompressed to produce an effective scavenging of the gases left in the residual volume.

Note that the intake volume is equal to the volume trapped by the free piston when it is fully displaced. The power density will not be as large as in the similar four-stroke engine and the mixture burned per cycle is about one-sixth that of a four-stroke engine, although at twice the frequency. The expansion ratio is only about 6 (see Table 1 in Ref. 1). The power output is about one-third of that of a four-stroke engine of the same displacement. The efficiency will be a little lower, but the engine will not have the problems associated with compression

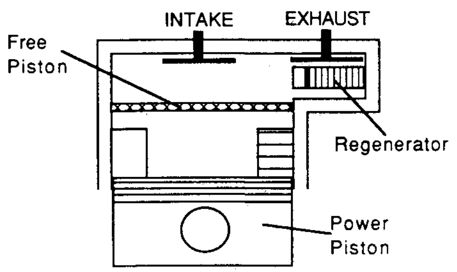

Fig. 1 Bowl-piston four-stroke regenerative engine.

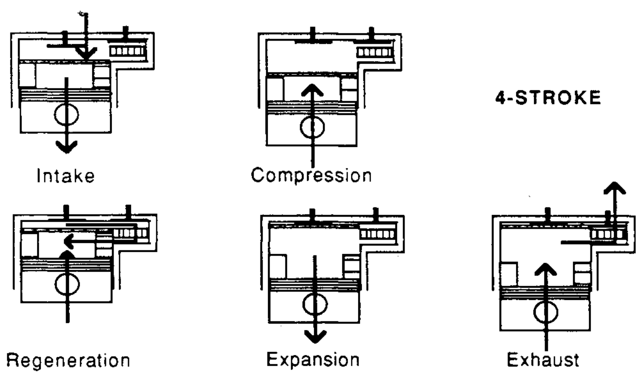

Fig. 2 Operation of the bowl-piston four-stroke regenerative engine.

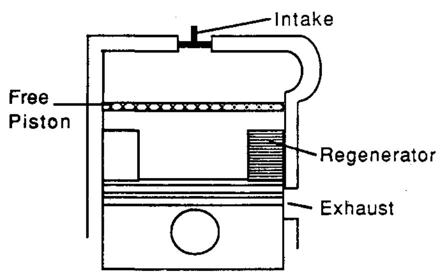

Fig. 3 Bowl-piston two-stroke regenerative engine.

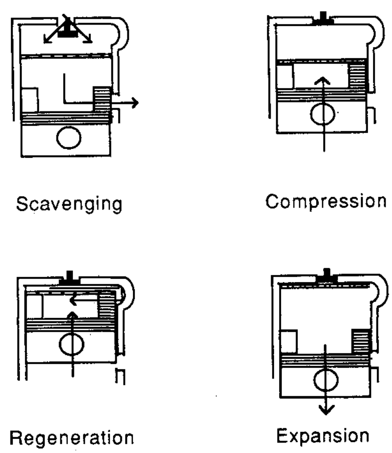

Fig. 4 Operation of the bowl-piston two-stroke regenerative engine.

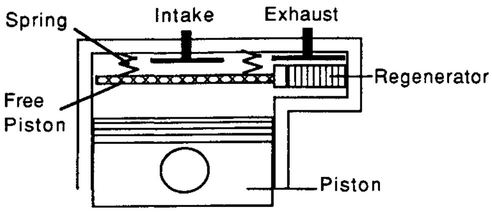

Fig. 5 Atmospheric regenerative engine.

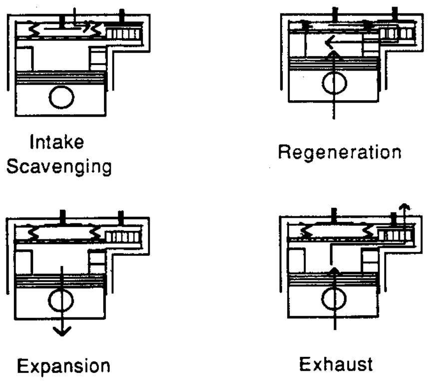

Fig. 6 Operation of the atmospheric engine.

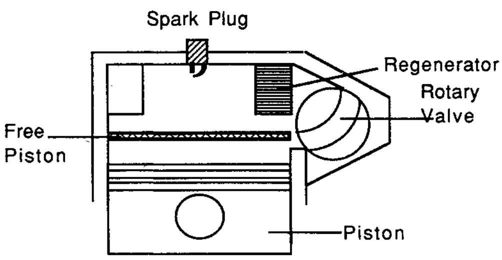

Fig. 7 Flat-piston four-stroke regenerative engine (homogeneous charge).

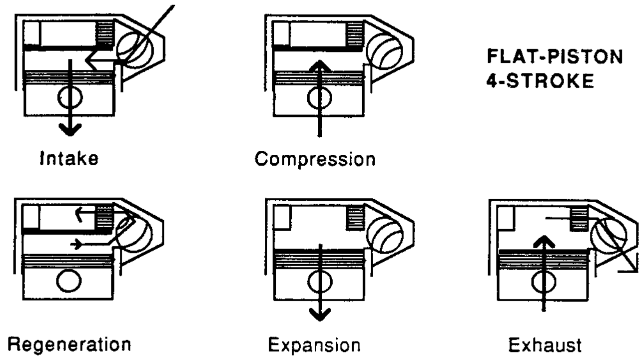

Fig. 8 Operation of the flat-piston four-stroke regenerative engine.

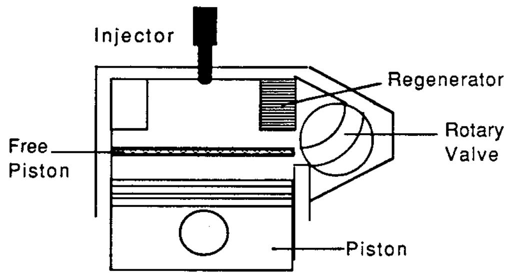

Fig. 9 Flat-piston two-stroke regenerative engine (direct injection).

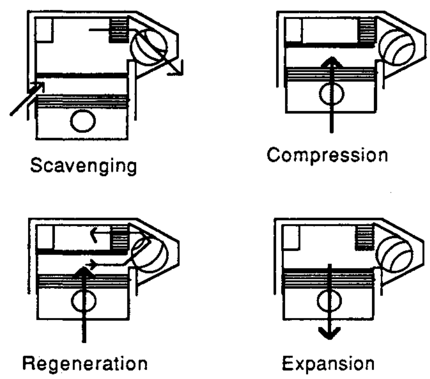

Fig. 10 Operation of the flat-piston two-stroke regenerative engine.

that all the other designs have to suffer. This engine will be appropriate to fixed installations in hard environments, where reliability can be of more importance than efficiency itself.

Flat-Piston Engines

Four-Stroke Engine

In this type of engine, the combustion chamber is carved out of the cylinder head and not into the piston. It will, therefore, be easier to insulate and will allow the use of more lightweight pistons. Figure 7 represents the four-stroke configuration. A valve system establishes communication between the compression and the combustion spaces and the exhaust and intake manifolds. The valve system will comprise three poppet valves (intake, exhaust, and transfer) or a single rotary valve. Rotary valves have had problems of reliability in the past due to prolonged exposure of their rubbing surfaces to the hot combustion gases,[4] but these problems are lesser here because the surface is never exposed to the burning gases. The sequence of events of this engine has been schematically drawn in Fig. 8. In this case, there is no problem with the motion of the free piston because it is either stationary, pushed upward by the other piston, or moved by strong pressure forces (the combustion pressure, during the expansion stroke). The free piston will act as a shield for the power piston, which can be made of a material less resistant to heat (an aluminum alloy, for instance). The combustion chamber should have a ceramic insulation.

Two-Stroke Engine

This configuration is shown in Fig. 9, which represents a direct fuel-injected engine, rather than a homogeneous charge engine. The flat-piston configurations are particularly suitable for fuel injection, presenting considerable freedom in selecting a location for the injector. The sequence of events in this engine is shown in Fig. 10. There is no great difference between this and its four-stroke counterpart, except for the intake port near the piston crown position at the bottom of the stroke and the fact that the distribution valve now rotates twice as fast, at crankshaft speed. The intake manifold is not connected to the rotary valve in this case.

Two-Piston Engine

The two-piston arrangement is schematically shown in Fig. 11. There is a phase difference of α degrees of crank angle between the two pistons. One of them compresses the mixture, then passes it through the regenerator to the other cylinder, where combustion and expansion occur. The flow of gases in and out of the engine is controlled by a system of valves, which also establishes communication between the cylinders during a few degrees near TDC. In this case, a rotary valve would never be exposed to the combustion gases, which makes its design less critical than in the other configurations. The sequence of events is shown in Fig. 12.

This configuration closely resembes some Stirling engines currently being developed by Ford, United Stirling, M.A.N., and others,[2,3] but here the combustion is internal, and there is gas exchange in and out of the cylinders, but not heat transfer. Like in the Stirling engines mentioned, the most advantageous design would be a double-acting layout, in which the upper chambers are reserved for expansion and the lower chambers for compression. The cylinders can be mounted in line, with the valve system on one side, or around a rotating swashplate, which also carries one rotary valve common to all of the cylinders.

The combustion chamber should be insulated (at least, the cylinder head), as well as the piston crowns. Plenty of development effort has been made for Stirling engines that can be used for this internal combustion engine. Some of the problems proper to the Stirling engine, such as no-leak sealing, heat transfer through the walls, and metallurgical limits for heat-transfer surfaces, are not present here. The main difference between the design of those Stirling engines and the regenerative engine is that the walls of the latter should be insulated, not heat conductive like those in the Stirling engines.

The optimum phase difference between the pistons will be somewhere between 30 and 90 deg of crank angle. Walker[2] points out that, for multicylinder double-acting Stirling engines, the optimum phase difference is somewhere between 60 and 90 deg of crank angle. The different cycle of the regenerative internal combustion engine (adiabatic compression and expansion) is expected to cause the optimum phase difference to be a smaller value. As a first approximation, we can assume that communication is established between the two cylinders from the moment in which the expansion piston reaches TDC to the moment in which the compression piston reaches TDC, α crank-angle degrees later. The compression ratio r would then be

$$r = \left(\frac{1 - \cos\alpha}{2}\right)^{-1} = \sin^{-2}\frac{\alpha}{2}$$

For $\alpha = 90$ deg, we get $r = 2$, but for $\alpha = 60$ deg, $r = 4$, and for $\alpha = 45$ deg, $r = 6.82$. The last value of r gives a better efficiency than the first two values for a regenerator effectiveness $\epsilon < 0.9$ (see Fig. 3 in Ref. 1).

Divided-Chamber Engines

This engine configuration, which does not have a free piston but has a fixed separation between the compression and expansion chambers, embodies the regenerative Diesel cycle, rather than the regenerative Otto cycle. A schematic drawing is shown in Fig. 13.

The compression chamber is communicated with the displaced volume through the regenerator and a passage controlled by a rotary valve. The passage is open only during the compression stroke. The phases of the cycle are represented in Fig. 14. In this case, all of the mixture is compressed into the upper chamber. Ignition does not occur. After TDC, the mixture flows through the regenerator into the displaced volume, where it burns and expands. The pressure in the cylinder must be smaller than that in the upper chamber, since there must exist a pressure difference for the mixture to flow through the regenerator. The pressure slowly decays as the mixture is burned until most of the fuel is depleted, near bottom dead center. When the exhaust is opened, the products of combustion flow back through the regenerator, igniting the residual mixture in the upper chamber.

The efficiency of the cycle used by this configuration is smaller than that of the others.[1] The only real advantage of this engine comes from the absence of a free piston.

Possible Practical Problems

Even from the theoretical stage, several problems can be foreseen that will need to be overcome in order to make practical the regenerative engine cycle.

Materials

Temperatures higher than those in the conventional Otto cycle will be reached. Some parts of the engine (the regenerator, for instance) are constantly subject to large temperature

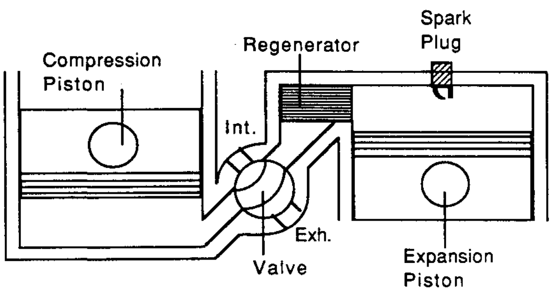

Fig. 11 Two-piston regenerative engine (homogeneous charge).

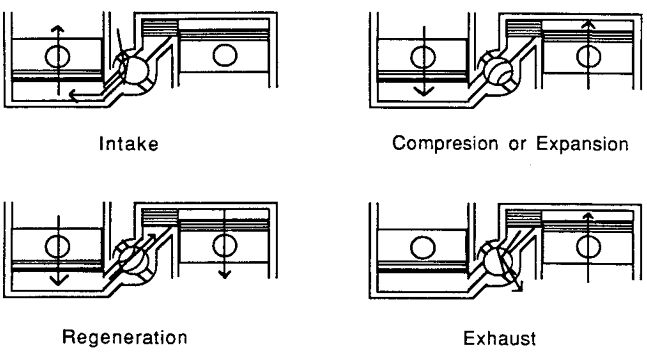

Fig. 12 Operation of the two-piston engine.

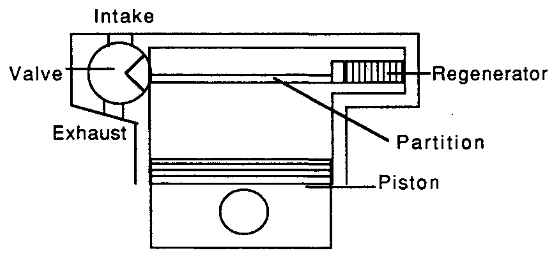

Fig. 13 Divided-chamber regenerative engine.

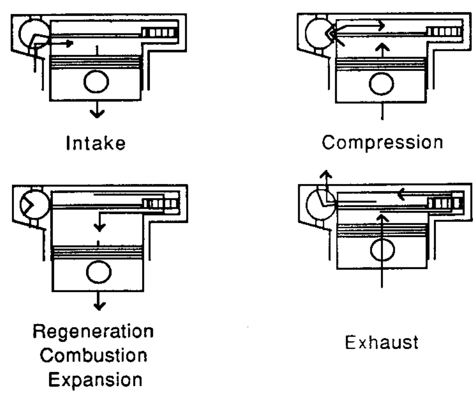

Fig. 14 Operation of the divided-chamber regenerative engine.

gradients, and the thermal stresses associated with them could threaten their integrity.

As a consequence of this higher combustion temperature, tribological problems may appear. The lubrication of the piston within the cylinder will be more difficult than in the normal spark ignition engine. The power cylinder of the two-piston configuration is constantly subject to a high temperature; conventional oil lubrication may not be possible. In the other configurations, the cylinder walls can be cooled by the incoming fresh mixture, and the lubrication problem will be less severe. It will not be convenient to thermally insulate the cylinder (except for the power cylinder of a two-piston-type engine) because the insulation would absorb heat during the expansion stroke, to release it during the compression, thus increasing the compression work.

The flow of gases through the regenerator may give rise to deposit buildup, which can eventually clog the regenerator, causing the engine to fail. This problem is also encountered in regenerators for gas turbines and catalytic converters. This problem poses a stringent requirement also to the cleanliness of the fuel; fuels with a high content of nonvolatile matter or that produce soot should be avoided. Those fuels should only be used in direct fuel-injected engines with wide regenerator cells so that the particles can be expelled to the exhaust without getting trapped in the regenerator.

NO_x Formation

A high combustion temperature is beneficial to the efficiency, but its byproduct is a high rate of formation of NO, which will later turn into NO_2. The NO_x emissions can be cut by exhaust gas recirculation or lean-burning mixtures that produce lower combustion temperatures. However, as is explained in the theoretical analysis,[1] reducing the combustion temperature lowers the benefit of regeneration and may even cause the regenerator to rob heat from the cycle to put it into the exhaust gases. Exhaust aftertreatment in a catalytic converter would be a better solution if the air-fuel mixture is maintained near stoichiometric proportions. The exhaust temperature of the regenerative engine is rather low (740 K for the sample data being used in Ref. 1) and could not be sufficient for the light-off of the converter. A third alternative is utilizing the regenerator itself as a catalytic converter.

Hydrocarbon Emissions

Since the typical hydraulic diameter of the regenerator (300 μ and less) will be smaller than the combustion quenching distance, the fuel remaining in the void volume of the regenerator and its feeding passages will have difficulty igniting and may be exhausted without having burned. This effect, which would produce a high level of hydrocarbon emissions, can be reduced by allowing the "cold" side of the regenerator to come in contact with the combustion gases for a brief period during the expansion, so that the fresh gases trapped can ignite. Another solution is placing the starting spark plug in this space and maintaining a fixed-timing spark a few degrees after TDC. At that time, all regenerative combustion should have been completed, and only the trapped mixture would be ignited by the spark.

Deviations from the Ideal Cycle

The most important differences between the real cycle and those analyzed by the ideal model[1] are expected to consist of the following:

1) Regenerative heat release not at a constant volume. It takes some time for the regeneration phase to occur, during which the piston moves. Inclusion of this effect would require a more detailed model than that presented in our theory.[1]

2) Substantial heat loss during expansion. This will be more severe than in a spark ignition engine, but can be reduced with the use of ceramic insulation. The regenerative engine has a different ignition process that makes it insensitive to knock.[1] Therefore, insulation will not negatively affect the combustion performance.

3) Pressure losses across the regenerator. If the cells are small enough to provide an effective heat transfer, they will also induce a significant pressure loss. In gas turbines, this effect is so severe that the regenerators used must often be more than twice the size of the basic engine. The pressure losses will vary roughly with the velocity to the power 3/2. These losses will become more severe as the engine speed increases, so that the operating speed will be limited.[1]

4) Other minor deviations, due to friction, irreversibility in compression and expansion, etc., will also be present, like in other types of engine. They do not seem to be more important than in spark ignition engines.

Concluding Remarks

1) There are two main families of regenerative engines: bowl-piston (combustion chamber carved into piston) and flat-piston (combustion chamber separate from piston). Both four-stroke and two-stroke designs have been described for either configuration.

2) All except two flat-piston designs are likely to be limited in speed during some phase of the cycle, due to the need to move a free piston only by pressure forces. Reduction of the weight of this piston is crucial.

3) Insulation is required in all cases for the combustion chamber. There is no risk of promoting detonation or increasing the compression work.

4) The two-stroke configurations can achieve a very high scavenging efficiency because the fresh mixture and the burned gases are physically separated at all times.

5) A two-piston design is possible that substantially draws on existing Stirling engine technology. The problems associated with this design are likely to be fewer than those found in the Stirling engine.

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