AC 2012-3107: EVOLUTION OF THE STIRLING CYCLE: EMPHASIS ON RELIABILITY, DURABILITY, AND LONG-TERM UNATTENDED OPERATION

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Abstract

The Stirling cycle is characterized by high efficiency coupled with the ability to effectively function on a range of heat sources. Included are industrial process waste heat, biomass, geothermal heat, and conventional combustion. Some of these sources are considered to be environmentally friendly, renewable, and have therefore interested researchers in the pursuit of pollution free or near pollution free electrical power generation. Drawbacks to the cycle include a high level of mechanism complexity which can impact reliability and durability. Further, the cycle demonstrates a relatively low power output per engine size when compared with that of other prime movers. Contemporary Stirling engine classification, Alpha, Beta or Gamma, is based on the physical layout of displacer and power cylinders with respect to a crankshaft. This report concerns a contemporary development of the Stirling cycle heat engine in which reliability, durability, and long term unattended operation are key objectives. To meet these objectives, the engine design focused on several factors which included: minimizing the number of moving parts, particularly reciprocating parts; incorporating materials not typically encountered in Stirling technology; use of liquid cooling; and, utilizing helium as the working fluid. The initial design parameters, e.g., phase angle, volume compression ratio, etc., were taken from those applicable to Gamma type engines. The literature suggests that Gamma engines represent state-of-the-art in the technology. Design efforts resulted in a working prototype with three moving parts per power cylinder. Included are a rotary displacer, a power piston and a connecting rod. Operation of the prototype demonstrated that Gamma design parameters were less than ideal for the new engine. This report summarizes the design elements of a new classification of Stirling engine and presents the results of optimization work to date.

Design Characteristics of Contemporary Stirling Cycle Engines

Contemporary Stirling cycle engines share design elements which, when reduced to the lowest common denominator, permit each to be classified as a particular type. There are three, the Alpha, the Beta and the Gamma.

The Alpha Stirling engine contains two power pistons. Each piston has an individual connecting rod and cylinder. One power piston and cylinder represents hot workspace, the other represents cold workspace. The two connecting rods join at a common journal on a single flywheel/crankshaft. This dual cylinder arrangement results in hot and cold workspaces which are physically separated. This feature provides excellent thermal isolation for the two workspaces, however, the conduit that joins the two workspaces can add to the dead space associated with the Alpha type. The Alpha then, in its simplest form, utilizes four reciprocating parts and one rotary part. Power pistons operate with relatively gas-tight seals within their respective cylinders. This prevents leakage of the working fluid and is not an issue for those components operating within the cold workspace. The hot workspace piston and cylinder do encounter sealing issues because they function in an environment with high heat as well as sliding friction. Seals on this piston can be subject to early failure due to these operating conditions. Techniques that alleviate hot piston seal failure issues may also increase engine dead space. Regardless, the Alpha is known for its high power-to-volume ratio.¹ ² ³
The Beta Stirling engine includes design features that eliminated the hot seal failure issues of the Alpha. The engine utilizes a power piston with a connecting rod, similar to the “cold” power piston of the Alpha, but the “hot” power piston in the Beta is replaced by a displacer with a connecting rod. The displacer represents a major improvement in that it does not require a tight seal along its surfaces as would a piston. The power piston and the displacer both share a common cylinder and a common flywheel/crankshaft. The function of the displacer is simply to shuttle working fluid within the hot and cold workspaces. A design in which there is sharing of a common cylinder presents thermal conduction issues not encountered in the Alpha. The junction of Beta hot and cold workspaces must include an additional thermal barrier to reduce thermal conduction and thus maintain efficiency. The sharing of a common cylinder in the Beta Stirling also has the advantage of dead space reduction as compared with the Alpha. The Beta, in its simplest form, consists of four reciprocating parts and one rotary part.\textsuperscript{1,2,4}

The Gamma Stirling engine is similar to the Beta in that it makes use of the same moving parts with a single, but major, difference. The Gamma power piston does not share a common cylinder with the displacer. The design employs two distinct cylinders. The displacer, which has no need of tight tolerance fitting within its cylinder, shuttles working fluid from the hot to cold workspace. The seals associated with the power piston do not have to contend with high heat and sliding friction. Again, hot and cold workspaces of the displacer cylinder require the addition of a thermal barrier. Therefore, in its simplest form, the Gamma configuration also consists of four reciprocating parts and one rotary part. The Gamma shares the same advantages as the Beta and also holds the potential for being mechanically simpler. Gammas are particularly suited to multi-cylinder applications.\textsuperscript{1,2,5,6}

In the preceding narrative, the reciprocating and rotating part count was always prefaced by the phrase “in its simplest form”. The reality of conventional commercial Stirling design seldom if ever adheres to the simplest form. Contemporary engines display a range of mechanisms, some fairly complex. Theoretically, however, Alpha, Beta and Gamma engines, in their simplest form, utilize four reciprocating parts and one rotary part per power cylinder.

**Designing the Stirling With Attitude (SWATT) Engine**

The author has designed and built a number of Gamma Stirling engines, all functioned, some better than others. Each was intended to represent an improvement over the previous, but engine performance always seemed shy of expectation. There were recurring questions about the suitability of various design elements. For example: Are there any additional areas in the mechanism where sliding friction be reduced or eliminated? How can the reciprocating mass be reduced? Are there any ways in which heat transfer in the displacer cylinder can be improved? Eventually, attempts to optimize the traditional Gamma were abandoned in favor of a type of Stirling entirely different. The author became convinced that the Stirling cycle could be effectively represented with fewer than five moving parts per power cylinder. It was speculated that three parts would suffice. A reduction in parts, particularly reciprocating parts, held the potential for increased mechanism longevity and reduced complexity. The utilization of carefully selected structural materials, nontraditional in terms of Stirling applications (e.g.,
PolyEtherEtherKetone, Viton, titanium, etc.), was part of the solution. These materials, while superficially appearing to be incompatible in a heat engine, nevertheless possessed desirable mechanical and thermal properties. Further, these properties could also contribute to the engines ability to run unattended for extended periods. Plain bearings simplify the design but require special provision regarding lubrication, particularly if extended, unattended use is envisioned. The use of ball and/or roller bearings wherever possible would not only reduce friction over plain bearings but also contribute to mechanism longevity. High-speed precision bearings, however, are intolerant of various forms of lubricant failure easily induced in a heat engine. Their use strongly suggested liquid cooling. Incorporating liquid cooling was further desirable for its stabilizing influence on engine operating parameters, particularly, mean displacer hot and cold side temperatures. Although liquid cooling represented additional design complexity, it was thought viable for its other advantages. The literature describing contemporary commercial Stirling applications indicated that the working fluid of choice is a noble gas. Uniformity of thermal performance over a known operating temperature range would seem to be valued in spite of the difficulty in maintaining such an environment within a working engine. For this reason, helium was selected for the working fluid.

The author proposed that the engine consist of three moving parts, two reciprocating and one rotary. These are shown, schematically, in Figure 1. The reciprocating parts consist of the

![Figure 1: Schematic Representation of SWATT Engine](image)

power piston, shown in full section, and the connecting rod assembly. The rotary part was the displacer, which in the schematic is depicted by a single displacer segment (#1). Integrated into
the displacer is the crankshaft/flywheel and a valve mechanism. The valve mechanism is partially depicted in Figure 1 by the cold side port and the hot side port. The motion of the displacer segment opens and closes the hot and cold ports. The crankshaft/flywheel also incorporated provisions for teeming engines to provide a robust and uncomplicated means of achieving multi power cylinder configurations. Figure 2 is a schematic representation of the rotary displacer, shown in full section without the distraction of the reciprocating components.

Figure 2: Schematic Representation of Rotary Displacer Depicting the Valve Mechanism

The rotation of the displacer is clockwise. In the figure, the hot side port has just been “opened” and the cold side port has just been “closed”. Their combined effect is the power piston is moving “outwards” in the power cylinder.

There are no specifications available in the Stirling literature pertaining to an unclassified, rotary displacer type with valve actuated hot and cold ports. It was, therefore, tentatively assumed that the proposed new engine would most likely adhere to those parameters characteristic of air-cooled Gammas, the subject of the author’s earlier work. Some of these were constructed in the laboratory facilities at the author’s university. Utilizing their numbers guaranteed that the size of the machining equipment available would be sufficient for the proposed engine. These parameters included: power cylinder dimensions, phase angle, volume compression ratio, displacer cylinder volume, and displacer dimensions. The power cylinder bore and stroke were 1.000” X .625” (volume = .491 in³). The phase angle was set at 90°, an angle also frequently cited in the Gamma literature. The volume compression ratio was set at 1.244. The power cylinder displacement and the volume compression ratio established the
maximum volume of the rotary displacer at 2.009 in\(^3\). Materials selected included stainless steel for all major structural components, graphite for the piston, titanium for the connecting rod assembly and polymer for the rotary displacer. The following sections address design features of major components, specifically, the individual displacer segments, the rotary displacer assembly, the displacer housing, and a rotary valve mechanism.

**Individual Displacer Segments**

The rotary displacer of the SWATT engine is built up of sixteen PolyEtherEtherKetone (PEEK) polymer segments mounted along an axle which is suspended by three sets of ball bearings. The bearings accommodate both radial and thrust loads and are mounted in liquid cooled sections of the displacer housing ends. Displacer segments are individually balanced. Balancing is accomplished with six through holes in each segment. All balancing holes are filled with an insert in the form of a cylinder. The inserts were die cut from Viton (FKM) foam rubber sheet. Viton, a fluoroelastomer with closed cells, has a low density (3.5 to 6.5 lbs./ft.\(^3\)) and a relatively high resistance to heat (-10°F to +400°F).\(^7\) The Viton inserts enabled the precise balancing of displacer segments through reduction of segment mass without adding to the engines dead space. Figure 3 shows a partial assembly of the rotary displacer housing with the hot side of the housing and most of the displacer segments removed for clarity. Included in the assembly are the cold side housing, the right housing end and seal, the displacer axle and the first displacer segment. The segments have a stepped profile along about 180° of the outer circumference, a profile which is mirror imaged in the internal surfaces of the two-piece displacer housing. This profile increases the surface area of the hot and cold workspace enabling a more rapid isovolumetric heating (expansion) and cooling (compression) of a larger volume of working fluid. The center of each displacer segment is precision bored and provided with a broached keyway. These two features locate individual segments along the centerline of the displacer axle while preventing rotation about it. Individual segments are held in position along the axle by two retaining rings which restrict lateral movement within a controlled range. This enables the polymer segment to expand laterally as the engine warms, but, at the same time, prevents their sides from touching the stepped profile of the displacer housing which necessarily must be in very close proximity to minimize engine dead space. Incorporation of a segmented displacer having a stepped profile for enhancement of heat transfer area was possible because the displacer was rotary. PEEK has mechanical and thermal properties that make it ideal for this application. These include: tensile strength of 16 ksi, compressive strength of 20 ksi, maximum operating temperature of 480°F, thermal conductivity of 1.75 BTU-in./ft.\(^2\)-hr.-°F, and a coefficient of thermal expansion, 2.6 X 10\(^{-5}\)in./in./°F.\(^8\) Figure 4 shows the sixteen displacer segments, a sample of Viton inserts and other components which assemble into a single unit on the displacer axle.

Thus, PEEK is a very good insulator that will neither absorb nor transmit much in the way of thermal energy. It is also relatively strong for a polymer and has a high operating temperature ceiling. Like most polymers, however, it “grows” when heated and this growth is
Figure 3: Partial Assembly Consisting of the Cold Side Displacer Housing, Right Housing End, Displacer Axle and a Single Displacer Segment

Figure 4: Sixteen Displacer Segments, a Sample of Viton Inserts, Retaining Rings and Displacer End Plate with Fasteners.
The type of stainless steel used in the water cooled displacer housing is AISI 304 which has a much lower coefficient of thermal expansion, 9.6 \(\mu\) in./in.-°F. Because the displacer segments are individually located along the axis of the housing using retaining rings, their relatively large coefficient of expansion is of consequence for a relatively short lateral dimension, their individual thickness. This expansion is easily accommodated in the sizing of the corresponding workspace for a given segment, even though the stainless housing “grows” very little by comparison.

The Rotary Displacer Assembly

A rotary displacer provides two advantages over one which reciprocates; it reduces cycle power needs and it opens design options. Given the same vital statistics (power cylinder dimensions, phase angle, volume compression ratio, displacer cylinder volume, and displacer volume) reciprocating displacers consume more cycle energy than a rotary counterpart. In one complete revolution of the flywheel, the displacer must change direction twice. First it is accelerated, starting from 0°. Maximum velocity occurs at 90° and is followed by deceleration which continues until the displacer momentarily ceases to move at 180°. The same process is repeated with maximum velocity occurring at 270° followed by deceleration and a complete stop at 360°. Cycle energy is required each time the displacer is accelerated and decelerated. Contrast this with the operation of a rotary displacer. It has a mass which must be accelerated to operating speed but it never changes direction. No engine energy is lost due to the constant need to accelerate and decelerate just to complete a cycle. The mass of the rotary displacer also acts as part of the flywheel/crankshaft mass which is essential to the functioning of any Stirling engine. This is because the expansion process must store energy in the flywheel to augment the compression process.

Design options, particularly those concerned with material selection, represent another area impacted by the motion of the displacer. In the case of reciprocation displacers, minimizing their mass can influence material selection, perhaps to the point of compromising desirable thermal and mechanical properties. Displacers and their associated mechanical connections must not adversely contribute to this mass. However, their selection should also attempt to provide high stiffness, low thermal conductivity and high thermal resistance. There are several engineered resins, PEEK being only one example, that have more than adequate thermal and mechanical properties. Their mass, however, tends to add negatively to displacer mass. Thin wall metallics possess stiffness and low mass but have less than desirable thermal properties. Ceramics like zirconium phosphate have superior thermal properties and stiffness but are costly to obtain and difficult to machine. With reference to the reciprocating displacer, it is difficult to identify a cost effective material that offers a range of desirable characteristics and is also relatively inexpensive. A rotary displacer is not nearly so mass sensitive. With an appropriately designed axle and properly selected bearings, engineered resins with their enhanced mechanical and thermal properties become serious alternatives. Polymer processing technologies also allow for cost-effective innovations in design (e.g. injection molding as opposed to machining) and also features for increased surface area, the stepped profile. Shown in Figure 5 is the fully assembled, segmented rotary displacer. The view is from the left end, the lines across the top normal to the axle indicating the space between segments. The spacing allows for the thermal
expansion of the PEEK segments. The stepped profile of the displacer is clearly shown in this view.

The Displacer Housing

The displacer housing forms an enclosed stainless steel cylinder consisting of four major components. Each is thermally isolated from the others by PEEK seals. The only interior surfaces of this housing where working fluid is free to contact hot or cold metal is along the internal circumference (not including the ends) of the displacer housing, the profile of which is a mirror image of the rotary displacer. The displacer itself forms the inner circumference of the cylinder. Thus, the working fluid within the displacer is completely insulated from all metallic displacer components except for the hot and cold workspaces. Left and right displacer housing ends contain bearings and cooling passages for these as well as the cold workspace. The right hand end contains the rotary valve mechanism consisting of a hot workspace port and a cold workspace port (spaced about 180° apart) which are alternately opened and closed through the action of the first displacer segment. These ports connect the hot and cold workspaces with the power piston which is mounted onto the right housing end. Figure 6 shows this arrangement.

The hot workspace manifold shown here allows hot working fluid access to the power piston, but only during the expansion process of the cycle. At the opposite end of this manifold is the hot side port shown in figure 3. There is a corresponding cold side port but it is obscured by the displacer axle in figure 3. During the compression process, segment #1 inhibits the working fluid from backing through the hot workspace manifold. Rather, it must pass through the cold workspace manifold. The liquid cooled cold workspace manifold is integral with the power cylinder mounting flange which is part of the right side bearing housing. Provision has been incorporated into the interior profile of the displacer housing (both hot and cold sides) to

Figure 5: Fully Assembled Segmented Rotary Displacer
augment the heating and cooling of the working fluid. This provision, as previously noted in the discussion of the displacer, consists of a series of radial grooves. The housing grooves are 1/8 inch across and 1/8 inch deep. Each groove corresponds to one of the segments in the displacer assembly. The housing, with grooves and a maximum inside diameter of 2.5 inches, has a surface area of 58 in.$^2$. If the same housing (2.5 inch diameter) were without the grooves, it would have a surface area of 30 in.$^2$. The grooves increase the surface area available for heating and cooling by about 90%.

Instrumentation of the SWATT Engine

The engine is currently mounted on a test bed with connections for the cooling system and a propane burner for energy input. Five surface contact type K thermocouple probes display

Figure 6: Assembled SWATT Engine with Hot Side Displacer Housing and Upper and Lower Longitudinal Seals Removed
temperature data. Two probes monitor hot workspace, two cold workspace, and one power cylinder temperature. Probes are connected to a pair of Fluke 52 II digital thermometers and a single Fluke 51 II digital thermometer. This instrumentation provides data which is compiled to document: mean hot workspace temperature, mean cold workspace temperature, and mean difference in temperature ($\Delta T$). Engine rpm is displayed using a non-contact laser photo tachometer (Extech Model 1PX61), also mounted on the test bed. An environmental chamber, which will completely enclose the right side of the engine, is under construction at this writing. The chamber will permit operation on compressed helium. In its absence, the engine has been run over 150 hours using air as the working fluid. Although not an ideal choice, air has performed fairly well and provided some interesting statistics.

**Preliminary Run Findings**

The engine requires a warm up of approximately 3 minutes. A warm up period is universal among Stirling engines. The duration of 3 minutes is likely due to the design of the hot side displacer housing which was machined out of the solid. Thick in cross section, a significant reduction in warm up time may be possible should the housing be fabricated from rolled sheet.

A single-cylinder Stirling will not self start; the crankshaft/flywheel must be spun by an external starter. The rpm at start is about 500 to 550 and the mean $\Delta T$ from ambient is predictably 70°F. Following start up, the engine heats to a mean $\Delta T$ of 99°F and a sustained 800 – 850 rpm (maximum achieved rpm to date is 950). As previously mentioned, this engine was designed using Gamma statistics which included a phase angle of 90°. Initial engine runs using this were less than satisfactory (ceiling rpm of about 400). Phase angles being relatively easy to change, a series of crank disks having a range of phase angles ranging from 80° through 135° in increments of 5° were constructed and tested. Observation of tachometer readings using the various crank disks indicated the ideal phase angle was approximately 125°. This performance is based on the previous indicated parameters while using air as the working fluid, atmospheric buffering from below, and no regenerator. The mean $\Delta T$ at initial start is noteworthy. It has been documented on all engine tests utilizing the 125° phase angle.

**The Direction of Future Research Regarding this Engine**

The SWATT engine is intended for pressurized helium as the working fluid. This requires an enclosure to seal the engine in the area of the flywheel/crankshaft and power piston/cylinder assemblies. The rush to get the patentable aspects of the engine protected, however, took precedence over designing and building the enclosure. Although incomplete at this writing, when fabricated it will enable the continuation regarding the optimization of selected design parameters, e.g., volume compression ratio. The configuration of the rotary displacer will also be a significant aspect of future research regarding this engine. To date, no Stirling utilizes this feature, and it is believed to be key in terms of simplicity, reliability and power output. Of particular interest is the configuration of the first displacer segment which controls sequencing of hot and cold ports. Segment number one also is concerned with the duration of the opening and closing of ports and any overlap when both ports are simultaneously open. Another aspect of research not yet included on the engine is the regenerator. Incorporation of this feature, yet to be built, should impact positively on engine efficiency.
Once the above has been accomplished, it is the intention of the author to scale up the design and produce multiple copies of SWATT. These will be teamed to provide a multi-cylinder engine for further investigation.

References


