The Phase Angle Influence on the Operating Characteristics of Gamma Stirling Engine

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***Abstract* – This paper presents a computer simulation of Gamma Stirling engine in Gamma Stirling Engine Simulator software by JLB Enterprises and the influence of the phase angle on the operating characteristics.**

***Index terms* – Gamma Stirling engine, Stirling cycle, regenerator**

I. INTRODUCTION

The hot air engine was invented by reverend Robert Stirling and patented in 1816 (Fig. 1). Stirling and his brother made lots of improvements to the original patent, the most important was the significant raise of pressure and in 1845 all the Dundee foundry was equipped with Stirling engines.[4]

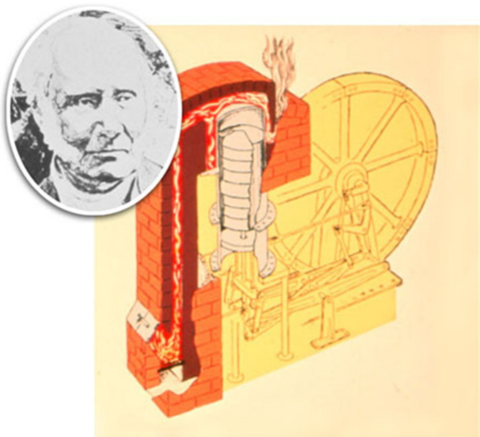

Fig. 1 Stirling engine patented in 1816
[reproduced according to 5]

II. STIRLING ENGINE CONFIGURATIONS

There are two major types of Stirling engines that are distinguished by the way that they move the air between the hot and cold sides of the cylinder:

The two piston alpha type design has pistons in independent cylinders, and gas is driven between the hot and cold spaces.

The displacement type Stirling engines, known as beta and gamma types, use an insulated mechanical displacer to push the working gas between the hot and cold sides of the cylinder. The displacer is long enough to thermally insulate the hot and cold sides of the cylinder and displace a large quantity of gas. It must have enough of a gap between the displacer and the cylinder wall to allow gas to easily flow around the displacer. [1]

An alpha Stirling (Fig. 2) contains two power pistons in separate cylinders, one hot and one cold. The hot cylinder is situated inside the high temperature heat exchanger and the cold cylinder is situated inside the low temperature heat exchanger. This type of engine has a high power-to-volume ratio but has technical problems due to the usually high temperature of the hot piston and the durability of its seals. In practice, this piston usually carries a large insulating head to move the seals away from the hot zone at the expense of some additional dead space. The following diagrams do not show internal heat exchangers in the compression and expansion spaces, which are needed to produce power. A regenerator would be placed in the pipe connecting the two cylinders.

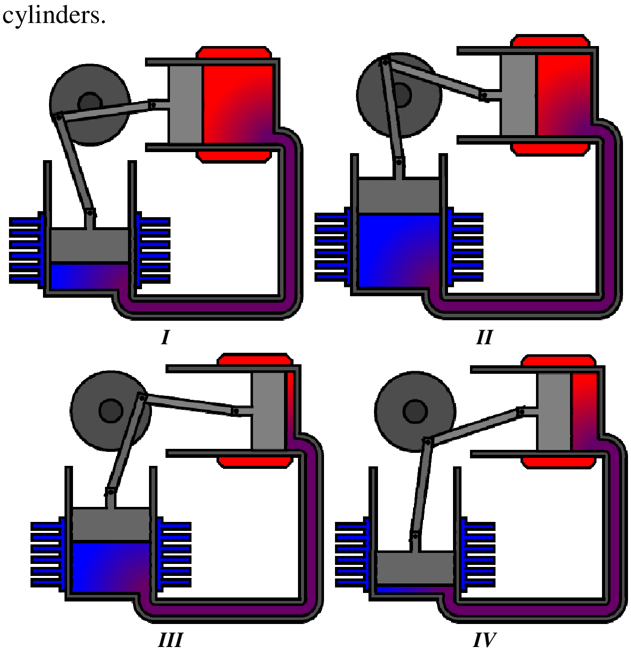

Fig. 2 The complete alpha type Stirling cycle
[reproduced according to 6]

A beta Stirling (Fig. 3) has a single power piston arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and does not extract any power from the expanding gas but only serves to shuttle the working gas from the hot heat exchanger to the cold heat exchanger. When the working gas is pushed to the hot end of the cylinder it expands and pushes the power piston. When it is pushed to the cold end of the cylinder it contracts and the momentum of the machine, usually enhanced by a flywheel, pushes the power piston the other way to compress the gas.

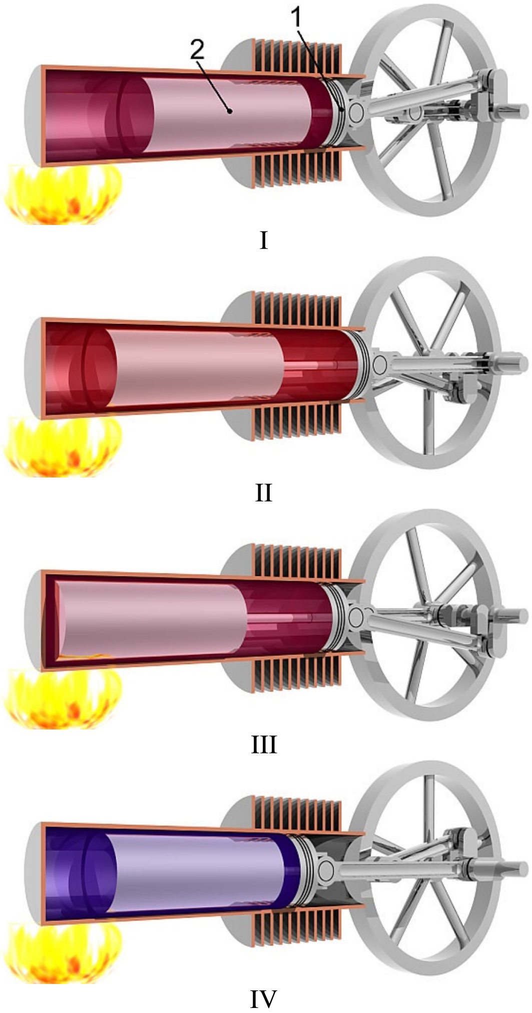

Fig. 3 The complete beta type Stirling cycle
[reproduced according to 5]

A gamma Stirling (Fig. 4) is simply a beta Stirling in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but is still connected to the same flywheel. The gas in the two cylinders can flow freely between them and remains a single body. This configuration produces a lower compression ratio but is mechanically simpler and often used in multi-cylinder Stirling engines. [2]

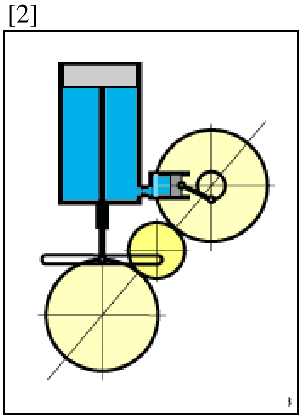

Fig. 4 The gamma Stirling engine
[reproduced according to 6]

Other Stirling configurations continue to interest engineers and inventors. Tom Peat conceived of a configuration that he likes to call a "Delta" type, although currently this designation is not widely recognized, having a displacer and two power pistons, one hot and one cold. There is also the rotary Stirling engine which seeks to convert power from the Stirling cycle directly into torque, similar to the rotary combustion engine. No practical engine has yet been built but a number of concepts, models and patents have been produced, such as the Quasiturbine engine.

Another alternative is the Fluidyne engine (Fluidyne heat pump), which use hydraulic pistons to implement the Stirling cycle. The work produced by a Fluidyne engine goes into pumping the liquid. In its simplest form, the engine contains a working gas, a liquid and two non-return valves.[2]

“Free piston" Stirling engines include those with liquid pistons and those with diaphragms as pistons. In a "free piston" device, energy may be added or removed by an electrical linear alternator, pump or other coaxial device. This sidesteps the need for a linkage, and reduces the number of moving parts. In some designs friction and wear are nearly eliminated by the use of non-contact gas bearings or very precise suspension through planar springs.

In the early 1960s, W.T. Beale invented a free piston version of the Stirling engine in order to overcome the difficulty of lubricating the crank mechanism. While the invention of the basic free piston Stirling engine is generally attributed to Beale, independent inventions of similar types of engines were made by E.H. Cooke-Yarborough and C. West at the Harwell Laboratories of the UKAERE. G.M. Benson also made important early contributions and patented many novel free-piston configurations (Fig. 5).

What appears to be the first mention of a Stirling cycle machine using freely moving components is a British patent disclosure in 1876. This machine was envisaged as a refrigerator. The first consumer product to utilize a free piston Stirling device was a portable refrigerator manufactured by Twinbird Corporation of Japan and offered in the US by Coleman in 2004.

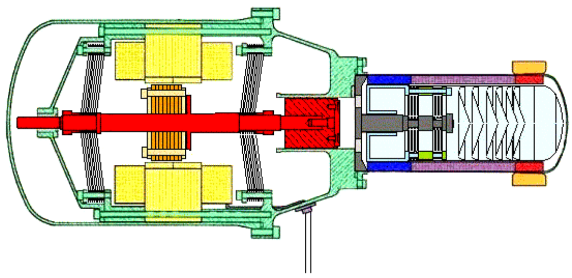

Fig. 5 The „free piston” Stirling engine
[reproduced according to 5]

Thermoacoustic devices are very different from Stirling devices, although the individual path travelled by each working gas molecule does follow a real Stirling cycle. These devices include the thermoacoustic engine and thermoacoustic refrigerator. High-amplitude acoustic standing waves cause compression and expansion analogous to a Stirling power piston, while out-of-phase acoustic travelling waves cause displacement along a temperature gradient, analogous to a Stirling displacer piston. Thus a thermoacoustic device typically does not have a displacer, as found in a beta or gamma Stirling.

III. THE PHASE ANGLE INFLUENCE ON THE OPERATING CHARACTERISTICS

For computer simulation of the Gamma Stirling engine and examining the operating characteristics and the phase angle influence over them, the software Gamma Stirling Engine Simulator by JLB Enterprises was used.

Some assumptions were made:

1) The bottom of the Displacer Cylinder is at the Hot temperature, and the top of the Displacer Cylinder is at the Cold temperature.

2) The temperature of the walls of the Displacer Cylinder varies linearly from hot on the bottom to cold on the top.

3) The temperature of the air in the Displacer Cylinder is the average of all of the wall temperatures.

4) The gas under the Displacer (the hot gas) is uniformly at the average exposed wall temperature.

5) The gas above the Displacer (the cold gas and the piston gas) is uniformly at the average exposed wall temperature.

6) The pressures in all parts of the Displacer, and the lower part of the piston, are all the same.

7) The pressure in the Displacer Cylinder is at ambient pressure at the time-averaged-mean of the internal engine pressure. This corresponds to the fact that most engines are not perfectly sealed, and will reach this pressure over time.

8) All physical analysis is "static"; the weights and moment of the Displacer and Piston are ignored.

9) The Piston is connected to a flywheel, but is not shown; the Piston and Displacer are not connected.

10) All of the calculations are unit less.

11) Pistons are considered to be weightless.

12) The Displacer moves up and down when the internal engine pressure rises above or falls below some pre-computed pressure values. Thus, the weight of the displacer is ignored, as is the cross-section of the displacer piston. [7]

As the simulator runs, values are computed based on the specified parameters. They are displayed in a stack of boxes in the upper right part of the screen:

- **Displacer Position**: the position of the Displacer, for the current phase angle; zero is down.
- **Position**: the position of the piston, for the current phase angle; zero is down.
- **Pressure**: the pressure inside the engine, for the current phase angle. More important than the pressure itself is whether the pressure is above or below the ambient pressure. This tells us whether the internal gas will be trying to “push” against the piston, or “pull” the piston. This is indicated by the trailing “(+)” or “(-)”.
- **Volume**: the total volume in the Displacer Cylinders, for the current phase angle. It is expressed as a percent of the total possible engine volume (maximum when the Piston is all the way up).
- **Hot N %**: this is the percent of the gas in the engine which is below the Displacer, for the current phase angle.
- **Cold N %**: this is the percent of the gas in the engine which is above the Displacer, for the current phase angle.
- **Maximum Pressure**: This is the maximum pressure achieved at any time during the engine cycle. It is the maximum over all phase angles. This value is not normalized.
- **Mean Pressure**: This is the time-averaged pressure in the engine. It is assumed that, over time, the pressure in the engine will try to equilibrate to the ambient pressure, because of small imperfections in the engine seals. We assume that the mean pressure and the ambient pressure will be the same. This value is not normalized.
- **Volume Ratio** is the ratio of the Displacer swept volume to the Piston swept volume. Large values are to be expected for low temperature (high efficiency) engines; values near 2 are to be expected for high temperature engines.
- **Temperature Ratio** is the ratio of the Hot vs Cold temperatures, expressed in Kelvin (absolute temperature). This is the same as the expected gas volume ratio when moved from cold to hot. Low temperature engines can have ratios around 0.01; high efficiency engines often have ratios near 1.
- The second **Temperature Ratio** is the same as above, only this time we take into account the fact that the walls of the Displacer Cylinder are not perfect insulators. As the Displacer gets shorter, more and more of the Displacer Cylinder walls are exposed, and the effective temperature ratio is reduced. This is that reduced ratio.
- **Theoretical Piston Throw** is our best guess at how far the Piston should travel. This value is computed by setting the engine to the design temperature with the Displacer and Piston at the bottom (zero) location, and then pulling the Displacer up (with the Displacer not connected to the Piston). The resulting gas expansion should push the Piston up the indicated distance. The two values correspond to the two different Temperature Ratios.
- **Net Work**: As the engine turns, the pressure from the gas on the piston is at times positive (in the same direction as the piston is moving) and sometimes is negative. If we sum all of the work (both positive and negative) over an entire engine cycle, we see whether the gases will “push” the piston more than they “pull” it. This tells us whether the engine will put out net power for us, or will stop running completely. The configuration with the largest value should produce the most power.

All of those values can be found in the next graphs:

The **Normalized Position Graph** shows the positions of the displacer and piston at each point during the engine’s cycle. The curves are simple sine waves, with the phase difference as specified by the Phase Offset parameter (Fig.6)

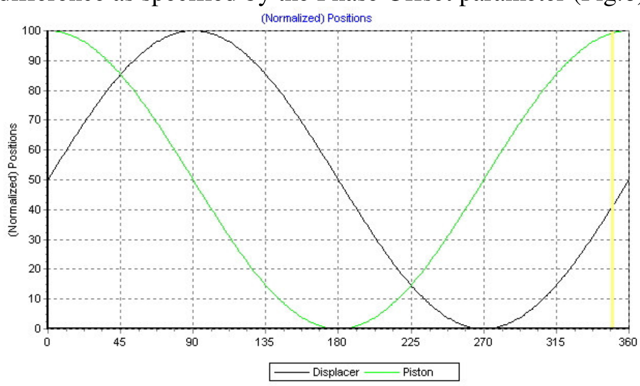

Fig. 6 Normalized position

The **Normalized Volume and Pressure Graph** is derived from the Position data. Once the position of the Displacer and Piston is known, we can easily compute the volume above and below the Displacer. This is the graphed Hot Volume (below the Displacer) and the Cold Volume (above the Displacer). The Total Volume is just the sum of the Hot Volume and the Cold Volume at each phase angle. The three volumes are not affected by the temperatures, but they are affected by the phase offset, the Displacer Cylinder diameter and height, and the Piston diameter and throw. Play with these parameters and watch how they affect the volumes, until it begins to make sense to you. You can adjust the temperatures to assure yourself that this does not affect the volumes.

The Pressure is a bit more complicated. Since we divide the Displacer Cylinder into two parts with the Displacer, we have two gas volumes at different temperatures (and usually with different volumes). The pressure will depend on both how “compressed” the gas is relative to the rest volume (Total Volume vs. rest volume); but it will also depend on how much of the gas is in the hot volume and how much is in the cold volume.

Consider the situation where the Hot and Cold Volumes are equal (Displacer centered, if the Piston is down): if the temperatures are equal, there will be equal amounts of gas in each volume. But the hotter the hot volume is, the more gas gets forced out of the hot volume and into the cold volume (i.e., forced from below the Displacer to above it). And the more gas gets forced out from below the Displacer, the greater the pressure in both cylinders.

There is one more complicating factor. We know the temperatures of the top and bottom of the Displacer Cylinder, since they are part of the engine parameters. As the Displacer gets shorter, more and more of the Displacer Cylinder walls are exposed, and since they cannot be perfect insulators, they modify the actual temperatures above and below the Displacer. We assume that the temperature of the Displacer Cylinder walls varies linearly from the hot temperature on the bottom to the cold temperature at the top. We further assume that the temperature of the gas is equal to the average temperature of the Displacer Cylinder walls.

The **Gas Temperature and Distribution Graph** shows where the gas is at each phase of the engine’s operation. This is shown by the thick curves as a percentage of total gas in the engine. This graph is affected by every parameter (Fig. 7)

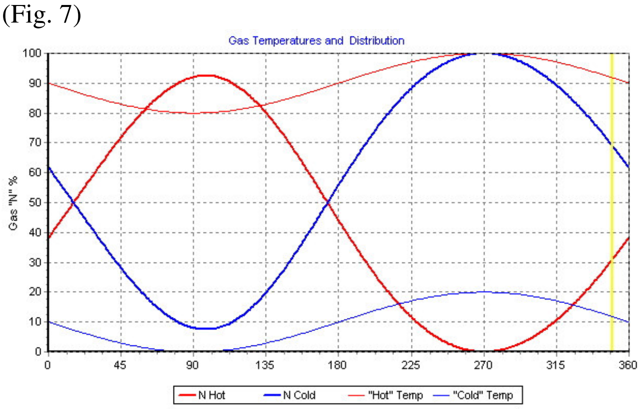

Fig. 7 Gas temperatures and distribution

If you start with the original settings and increase the hot temperature, you will notice that more of the gas gets forced into the hot/cold volumes at the appropriate parts of the cycle, with almost all of the gas in the Hot volume at a phase angle of 90°, and almost all of the gas in the Cold volume at a phase angle of 270°.

If you change the Piston Throw from 0.4 to 4.0, you will notice that at 90° degrees, the curves begin to move away from 100 percent. This is because, by making the piston larger, we have increased the “dead volume”, making it impossible to get all of the working gas into the hot part of the engine. When you are done, return the Piston Throw value to 0.4.

The thin curves show the effect of the Displacer Cylinder walls on the actual temperature of the gas. If you change the Displacer Height from 0.6 to 0.9, you will see that these thin curves snug up more tightly against the top and bottom of the graph. As less and less cylinder wall is exposed, the gases maintain the maximum temperature differences.

Once we know where the gas is in the engine, and what the current volume is, we can compute the total pressure in the engine. This curve is shown on the Volume and Pressure Graph (Fig. 8). The dark horizontal line shows the mean Pressure, which is assumed to be the ambient pressure. This value will be used in a moment.

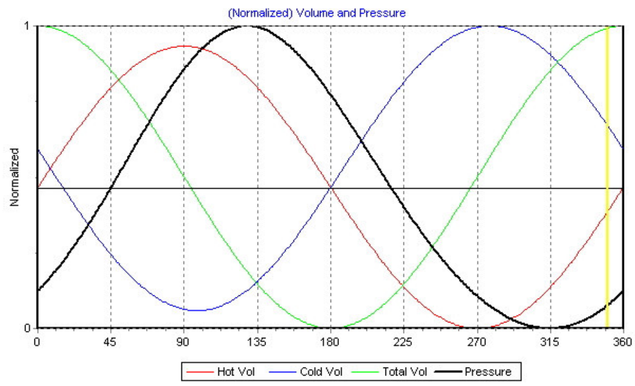

Fig. 8 Normalized volume and pressure

Note that the graphed Pressure value is “normalized”. This means that it is scaled so that it goes from a value of zero to a value of one. This helps us graph more than one value on a single graph without having to worry about lots of different scales. If you want to know how large the pressure peak is, you can look the Maximum Pressure value listed in the upper right of the screen.

Return the Displacer height back to 0.6 and look at the Pressure curve. Notice that it sits almost on top of the red (hot volume) curve. This says that whenever a lot of gas is in the hot part of the engine, the pressure rises, because the gas is heated by the bottom of the displacer.

Now, change the Piston Throw back from 0.4 to 4.0, and notice what happens to the Pressure curve: it shifts left by some 50 degrees. This is because when we made the Piston motion larger, it changed from being insignificant to being important. As the Piston moves up and down, it compresses the gas on the down stroke, and expands it on the up stroke. The two competing effects (the gas heating up from the bottom of the Displacer Cylinder and the Piston motion) combine to shift the pressure curve to the left.

The **Work Graph** is the key to determining whether a particular engine configuration will generate energy (do work). As the Displacer and Piston move in their cycles, at some moments the internal gas is at a higher pressure than the ambient pressure; at other moments, the internal pressure is less than ambient. If the piston is moving down when the internal pressure is high, energy will be contributed to the flywheel; similarly if the piston is moving up when the internal pressure is low. If the reverse situation obtains (piston moving down with low internal pressure, or up with high pressure), the pistons take energy from the flywheel. If the engine contributes more energy to the flywheel over the entire cycle than it removes from the flywheel, the engine will continue to run; any excess energy is available to do work for us.

The graph is calculated as follows. At each phase angle, the internal engine pressure is determined and compared to the ambient/external pressure. If the internal pressure is higher, this is indicated with a "(+)" to the right of the Pressure value provided on the upper right of the screen. The direction of the piston is then noted, and if it is moving in the "right" direction (as discussed in the previous paragraph), the engine pressure is deemed to be contributing to helping the engine work; the force is positive.

Knowing whether the internal gas is "helping" the pistons is useful, but the amount of "Work" which the engine does is pressure (force) times distance. (Fig. 9) We compute how much work each piston contributes (or takes) by multiplying the internal pressure (relative to ambient) by the piston motion.

This takes the following into account. Consider the following diagram:

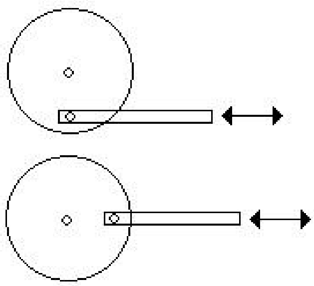

Fig. 9 Crankshaft [reproduced according to 6]

Here we see a wheel (crankshaft) driven by a push rod. The wheel position differs by 90 degrees in the two images. Imagine trying to push on the rod in the top case: the wheel turns easily, accepting the energy you are putting into it. But in the bottom case, nothing happens: whether you push or pull, all of the force works directly against the axle, and the wheel does not turn at all. The "effective energy" which is applied to the wheel is a sine function of the applied energy: the rest is wasted. A similar effect takes place with our engine. Put another way, you can push as hard as you want in the bottom diagram, and you will do no work; you do the most work (for a given push) in the top diagram.

The Work Graph shows how much each piston is contributing to helping the flywheel turn. This takes into account 1) the internal engine pressure, relative to the ambient pressure at each phase angle; 2) the direction in which each piston is moving at any given phase angle; and 3) the amount the piston is moving at the given phase angle. The result is the blue Work curve (Fig. 10)

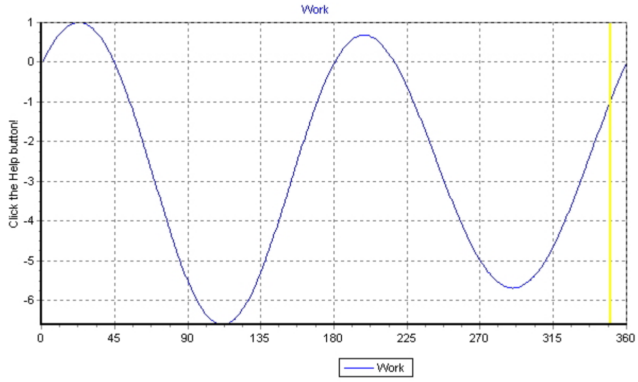

Fig. 10 Gas temperatures and distribution

Notice that in the current configuration the blue line goes through zero four times every cycle. This is due to two things: the fact that the piston stops moving at the top and bottom of its motion each cycle, and the fact that the pressure passes through zero twice every cycle. If you click on the Piston Position Graph where the curve hits the maximum (180 degrees), you will see that the Work Graph also passes through zero at that phase angle. This is also true for phase angle 0, where the piston is at the other end of its stroke. Click where the pressure graph passes through zero (120 and 305 degrees) and you will see that the Work graph also passes through zero at these times: this is because at that instant, the internal engine gas can neither push nor pull on the pistons.

If you restore the Piston Throw to 0.4, you will see that the Work graph changes so that it only hits zero at two points (roughly 0 and 180 degrees). This is because the Pressure graph shifted back to the right, and now the Piston motion zeros coincide with the Pressure zeros.

The dependence of the phase angle depending on the pressure is presented below in Fig. 11:

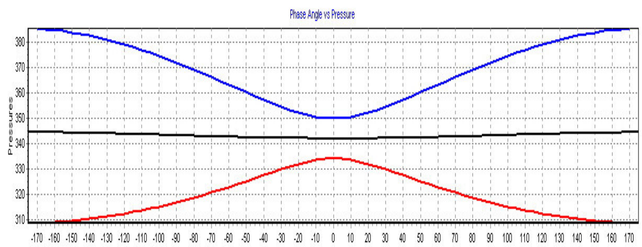

Fig. 11 Dependence of the phase angle vs pressure

In the figures presented below (Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16) we can observe the phase angle influence on the PV diagrams for the phase offset values: 0°, 45°, 90°, 135°, 175°.

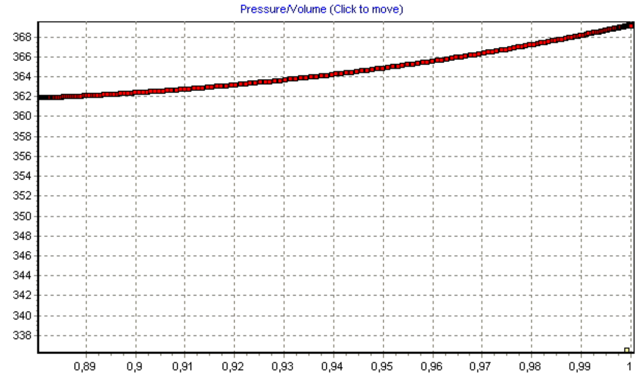

Fig. 12 PV diagram (phase angle is 0°)

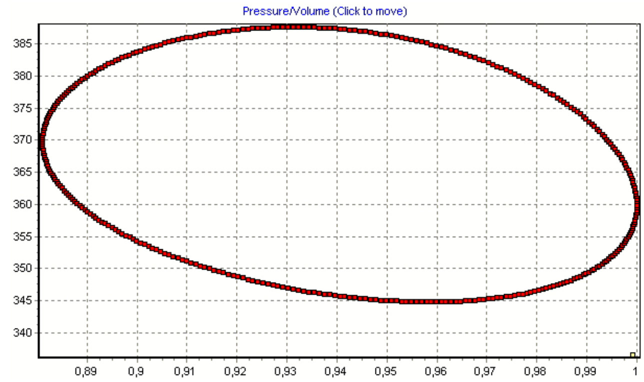

Fig. 13 PV diagram (phase angle is 45°)

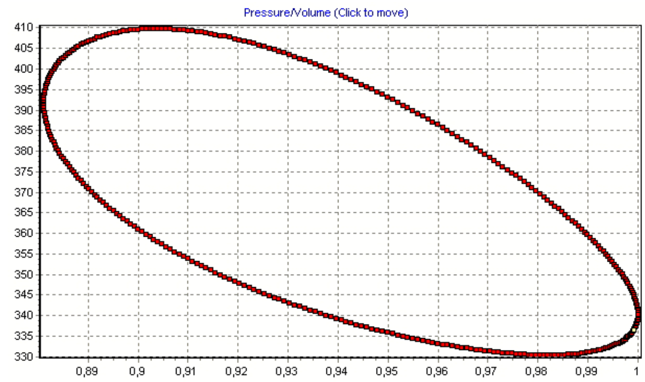

Fig. 14 PV diagram (phase angle is 90°)

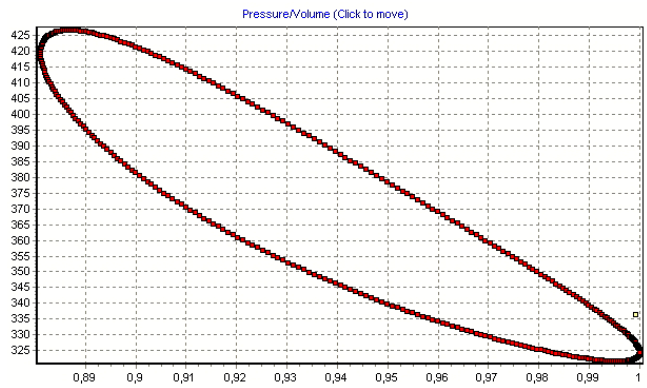

Fig. 15 PV diagram (phase angle is 135°)

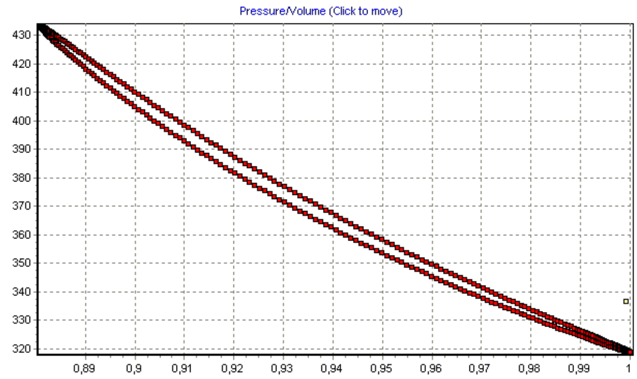

Fig. 16 PV diagram (phase angle is 175°)

IV. CONCLUSION

- The heat is external and the burning of a fuel-air mixture can be more accurately controlled.
- They can run directly on any available heat source, not just one produced by combustion, so they can be employed to run on heat from solar, geothermal, biological or nuclear sources.
- Most types of Stirling engines have the bearing and seals on the cool side; consequently, they require less lubricant and last significantly longer between overhauls than other reciprocating engine types.[3]
- The engine as a whole is much less complex than other reciprocating engine types. No valves are needed. Fuel and intake systems are very simple.
- They operate at relatively low pressure and thus are much safer than typical steam engines.[8]
- Low operating pressure allows the usage of less robust cylinders and of less weight.
- They can be built to run very quietly and without air, for use in submarines.

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