DOE/R4/10097--T1

R2
10097

DOE/R4/10097--T1

DE84 000744

Final Report
of
Department of Energy
Appropriate Technology Small Grants Program
Grant No. DE-FG-44-80R4-10097.000
for the
✓ Development and Testing
of a
Rotary Solar Engine

D. B. Kanaly, Grantee

12-0090

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Summary

A rotary solar engine has been constructed and tested. By sealing Freon (having the environmentally safe composition rather than the conventionally used harmful composition) in its bellows instead of air, sufficiently consistent operation can be achieved to serve the purely mechanical rotary light-load or no-load markets.

Although its power efficiency is not sufficient to make it competitive as a prime power generator, even for power outputs as low as a few ounce inches per minute, its simplicity and reliability make it an attractive self-powered source of mechanical control power for critical slow speed actuators. Its simplicity and low cost make it particularly attractive for the small (less than 10 in³) display markets. Other markets may now be identified, now that its strengths/limitations are known.

The Design Concept

As shown in Figure 1, the Rotary Solar Engine in its basic form consists of several bellows mounted between two end plates with the axis of each end plate mounted on a pair of bearings. With external forces, the two axes would be colinear (see Figure 1(a)). However, the two axes of the assembly are skewed by bending the assembly at the bellows as shown in Figure 1(b). To permit this bending, the bellows at the outside of the curve must expand, those on the inside must compress. Bellows at the top and bottom are of average length.

Upon heating the top bellows (by solar radiation), the air, or other gas, within it attempts to expand, causing it to move toward the outside, rotating the assembly and producing useful power.

As shown in Figure 1(c), rotation of the assembly creates its own control of the power cycle sequence since expanded (previously heated) bellows are rotated underneath into the shade (and when provided, into water) where they cool. To contract, these cooling bellows force their way to the inside, assisting in the production of useful power.

Background

The attraction of the concept is its simplicity: several bellows, two end plates, two pair of bearings. The only moving parts are the bearings. It is inherently low in cost. It obviously could be easily assembled, installed, operated, and maintained by the average person.

a) Assembly with colinear axes

b) Assembly, axes skewed, viewed from above

c) Assembly, axes skewed, viewed from front (horiz. plane)

Figure 1. The Basic Concept

A small prototype had been built and it had operated successfully, proving the concept. The prototype was too small to measure its performance.

Purpose of Grant

The object of U. S. Department of Energy Appropriate Technology Program Grant No. DE-FG44-80R410097 was to construct a larger model and measure its efficiency. It was felt by the grantee that any reasonable efficiency would make the concept practical for several simple low power tasks. Its simplicity would enable it to compete with the other more efficient but also more complex (costly) approaches. Although no hard criteria was set as to what was a reasonable efficiency, it was felt by the grantee that any efficiency above 1 percent would make it a marketable contender for many tasks.

Project Sequence and Report Organization

The project followed a general sequence of: Purchasing of materials, assembly, testing of the engine. However due to the need for repeated changes, the project included many preliminary tests followed by purchasing of new materials, reassembly, another preliminary test, etc., until the best configuration was ready for final tests. Therefore to make this report most useful for future investigators, the bulk of the report is organized around each major design consideration as they were encountered and describes what lessons were learned. These discussions are followed by final test results, conclusions and recommendations.

Length and Diameter of Bellows

Analyzing the rotary solar engine, we find that its simplicity tends to restrict its output power. As shown in Figure 2(a) the expansion force of each heated bellows can be resolved into two components: the useful component which is being applied to produce rotation in a direction allowed by the bearings, and an unproductive component which is attempting to produce rotation in a direction not allowed by the bearings. As shown in Figure 2(b) the greater the skew angle of the axes, the more useful output torque results from whatever expansion force is produced by the bellows (as a function of the sine of the angle). Of course the maximum output torque results when the skew angle is 90° which leads directly into a crankshaft and connecting rod mechanization. In avoiding the complexity of the crankshaft and connecting rods, the rotary solar engine is restricted to low skew angles. One goal becomes how to maximize the skew angle and still retain simplicity (and low cost).

Figure 2(a) The Two Components of a bellows' force, productive and unproductive

Figure 2(b) Three Skew Conditions and the Resulting Output Torque

FIGURE 2. Force from a Single Bellows in the Top Heating Position Converted to Useful Output Torque as a function of Skew Angle.

As shown in Figure 3, the first way to maximize the skew angle is to select bellows which have the maximum useful stroke (difference between expanded length and compressed length) for any given diameter. Of course, any given bellows design can have an increased stroke by simply increasing the length by additional convolutions, however excessive length causes buckling under load and sagging in unloaded conditions. Each bellows manufacturer advises as to practical limits for each type design.

Choice of Bellows Materials

The spring rate of the bellows should be minimized so that less of the expansion/contraction force is resisted by the material itself. Beryllium Copper (reference line 269 in Robertshaw Fulton Sylphon Catalog R) was selected as having the maximum stroke per diameter in a practical, low spring rate material of this size.

Bellows Ends

To connect each end of each bellows to the end plates, two alternatives were pursued. One was simply to repeat the design of the prototype which was to simply fasten each bellows end rigidly at right angles to the end plate as shown in Figure 4(a). There was no difference found whether spacers were used or not (as illustrated on the left and right sides of Figure 4(1), respectively). The obvious disadvantage of this firm fastening is that when the axes are bent, the bellows bow outward, reducing the amount of force from the bellows which can produce useful rotational force.

The alternative approach was an attempt to avoid this bowing and also maximize the skew angle as previously discussed. The bellows were attached to the end plates via spherical bearing rod ends, as shown in Figure 4(b). This was a moderate cost (rod ends cost approximately \$1.00 each, in quantity) compromise toward a full crankshaft connecting rod scheme which still retained most of the simplicity of the basic scheme. Unfortunately it created additional degrees of freedom, there was nothing to prevent one end plate to rotate (up to 40°) with respect to the other. A central bellows was added (with ridged end mountings) to prevent this motion. (The central bellows performed this task very well: it prevented the relative rotation, yet resisted bending of the axes very little and did not expand or compress during a cycle since it was in the center.)

Bellows Preload

When asking the bellows manufacturer what maximum stroke could be used, it was learned that for maximum life (number of stroke cycles)

Fig. 3(a) Maximum Stroke of a Given Bellows Design

Fig 3(b) Engine Rotor Assembly Skewed to Utilize Full Stroke of a given Bellows Design

FIGURE 3. The Effect of Bellows Stroke on Skew Angle

Bolted to End Plates
With Spacers

Bolted Directly
to End Plates

Fig 4(a) Firmly Fastening Bellows to End Plates

Studs, screwed into end plate periphery

Fig 4(b) Attaching Bellows to End Plates via Rod Ends

FIGURE 4. Mounting Bellows to End Plates, Two Alternate Methods

it is advised that the bellows be compressed more than it be expanded. Dividing total stroke into three parts, it is recommended that expansion be limited to 1 part, compression 2 parts. Therefore, a simple means was devised to force the end plates together placing the bellows under a compressed preload. Using the design with the rod ends and central bellows as the prime approach, a chain with adjustable length mountings was routed through (inside) the central bellows, drawing the two end plates toward each other. It was adjusted in length until the correct preload was achieved.

During this stage in the assembly, preliminary tests were conducted, rotating the solar engine by hand. The engine would rotate only when considerable torque was applied. The bellows preload was removed and less torque was required to rotate the assembly but it was still obvious that there was too much friction.

At this point, the simpler rigid bellows end mount design (as shown in Figure 4) was tested and found to require a small fraction of the torque to manually rotate. All further work was done using the rigid end mount design.

Assembly Prestress and Assembly Preloads

Two phenomena were noticed which need to be reported which revealed prestress and preloads which became apparent when the total engine is assembled:

The bellows were ordered with relief valves (brass needle air valves from an aquarium supplier worked very well); they were soldered to the bellows end caps.

With these valves open on the assembled engine, axes skewed, and the rotor spun from a manual flick of the finger, it was noticed that it would always come to rest in the same attitude (same bellows up, same on outside, etc.) behaving like a "Wheel of Fortune" with a heavy weight at one place on the rim. But it was not due to mass unbalance; because upon turning the entire engine upside down and spinning again, it would come to rest with each bellows in the same location relative to the engine frame, but with the opposite bellows uppermost, etc., relative to gravity. Upon further study, the explanation was simple: some of the bellows were longer than the others (when measured in an identically unladed condition); and the rotor would always come to rest with the three adjacent bellows having the longest average length grouped around the outside position of the skewed axes bend and the shorter three grouped at the inside.

Upon closing the valves with axes co-linear (each and every bellows neither compressed or expanded, but all bellows forced to be approximately the same length) and then skewing the axis and spinning the rotor, again the rotor would always come to rest in a favored attitude. But it was a different attitude from the one of the

previous tests, other bellows were outermost, others innermost. Upon further study it became clear that some bellows simply contained a slightly larger air volume than the others at the time of valve closure (for several reasons) and these bellows would seek the outside.

Due to the low spring rate of the beryllium copper bellows, with relief valves closed, the force differences due to entrapped air greatly overpowered the force differences due to length, and the longer entrapped volume always forced its way to the outside expanded position. Which, upon reflection is to be expected due to the very principal upon which the engine operates: the bellows requiring the larger volume, whether due to original volume or due to heating, will always seek the outside, expanded, position. This "assembly preload" was substantial. During later tests, if the preload was not removed, the engine would not operate at all, it would simply remain in its favored attitude.

Fortunately, the solution was simple: the manual valves were never closed until after the axes were skewed and then only as the rotor was turned to bring each bellows to the top position. At that point, that bellows' valve would be closed, and the next bellows brought to the top position, etc. (closing at the top position was found to produce superior performance). During testing it was also very obvious that if the rotor was allowed to come to rest in any one position and remain while some adjustment, etc., took place, then that attitude quickly became the preferred attitude. To remove this preference the rotor would have to be manually rotated for many minutes or the initialization valve shutting process just described would have to be repeated. It would have to be repeated until no preferred attitude could be found which usually took several cycles because after being left in the sun, thermal equilibrium would have to be restored throughout the rotor assembly, as well.

It is obvious that a better solution to this preload problem must be developed for a practical, simple, production design. This is discussed further at the end of the report.

Preliminary Tests and Design Improvements

Preliminary tests indicated very unsatisfactory results but also revealed potential improvements in the design. It was not clear that the combination of the changes would yield a sufficient performance improvement; to the contrary, it appeared unlikely that they would. However considering the investment in time and money already expended, it was worth reasonable efforts to implement any clear improvement and measure the results.

The basic preliminary test set-up consisted of the engine on a table in the sun with a plastic fresnel lens to concentrate the sunlight. The fresnel lens has an effective diameter of 12 inches and was used to concentrate light into a region which ranged from a minimum of $2\frac{1}{2}$ inches diameter, the size to cover a single bellows, to a maximum of 4 to 5 inches when it was desired to cover two bellows.

With this set-up, the engine would operate erratically by itself (no-load) but any attempt to measure the output power would stall the engine. Stall torque was insufficient to measure. The engine would not operate on direct sunlight, concentration was required. The following improvements were indicated:

1. The beryllium copper bellows should be oxidized black for improved solar absorption.
2. An adjustable reflector should be constructed (2 foot x 4 foot panel covered with Edmund Scientific #072031 Solar Sheet) which would be mounted overhead during testing and permit control of sunlight direction from overhead or from any other desired direction.
3. Provision should be made to protect the top of the rotor (being heated by the sunlight) from the cooling effects of wind.
4. A water pan should be placed underneath the engine to cool each bellows at the bottom of the cycle.

An internal reflector was also considered: it would reflect back toward the bellows sunlight which passed between adjacent bellows. However upon further consideration, it was clear from the geometry of the rotor that less than 10% of the sunlight can pass between the bellows. Therefore the added complication could only contribute a 10% improvement at best.

All of the above improvements had originally been planned to eventually be incorporated into the design. However, originally they had been viewed as techniques to optimize efficiency, and were to be incorporated one at a time, during a lengthy test phase of the program, separately measuring their contribution to efficiency. Whereas, now they were being added together at the beginning of the test phase in the hope that collectively they would raise efficiency to a useful level.

Test Results Using Air Within the Bellows (to be repeated later with Freon)

Using the lower friction rotor assembly (rigid bellows mountings) with blackened bellows, with protection from any ambient wind and a water pan beneath the rotor and with control of the direction and concentration of sunlight, tests were conducted to optimize several

variables. It was found that maximum output occurred with an axis skew angle of 6° per axis (12° between axes), and with the sunlight directly overhead when the skewed axes were in a horizontal plane, and the water level in the pan was at least deep enough to contact every convolution at the bottom of the cycle. Output was not highly sensitive to more water in the pan or changing the sunlight direction by $\pm 20^{\circ}$, but increasing the half skew angle beyond 8° per axis would stall the engine as would reducing it to less than 4° . Another variable having a slight effect was the amount of sunlight concentration using the fresnel lens. Maximum output occurred when a 12" circular column of light was concentrated to about 5" in diameter directly at the top center of the rotor. At this spot size, when one bellows is at the top of the cycle, the spot extends to both adjacent bellows and the top bellows is not being heated as much as if the light were concentrated to a 2.5 inch spot (the size of one bellows). However, 30° later in the cycle when two bellows are equidistant before and after the top of the cycle, the larger spot size covers both; and continuous heat for more than one bellows at a time and for each bellows further into the cycle appeared to more important than maximum but short dwell time heating. (This was true with air in the bellows, as will be seen, later, with Freon in the bellows, the reverse was true)

When the reflected unconcentrated sunlight intensity was 67 mw/cm^2 (measured with a Dodge Products Model 776 Solar Meter), which is strong unclouded sunlight, concentrated from 12" diameter to 5" diameter at the top center of the rotor, and all other variables adjusted for maximum output, as described, the rotor would advance steadily through one revolution in 80 to 90 seconds with no load. All attempts to measure power, and thereby efficiency, failed because even loads as light as 0.1 ounce inches produced erratic behavior (stalling followed by brief rapid turning, followed by stalling, etc.). Stall torque was 2.5 ounce inches. The engine would still not operate without sunlight concentration.

Freon in the Bellows

Consideration was being given to terminating the project, when it was realized that using Freon within the bellows instead of air should substantially improve performance. Although the type of Freon normally used today is environmentally unacceptable, there are compositions available which do not decompose ozone which are being produced for widespread future use.

The air in the bellows was replaced with Freon and the testing repeated. To purge the air while replacing it with Freon, the two valves on opposite ends of each bellows were opened, and Freon applied to the stem of one through a lossy connection. After allowing time for all the air to be forced by Freon out of the bellows, the downstream valve was closed (the lossy connection preventing over-

pressure of the bellows from the Freon source). The upstream valve was then closed and the Freon source removed. Then the upstream valve was reopened with the bellows in the top position on the rotor and by listening to the escaping Freon, the bellows was allowed to depressure to one atmosphere of pressure. The procedure was then repeated with the bellows on the opposite side of the rotor, then an adjacent bellows and its opposite, then the last two.

Test Results with Freon

The engine will operate with no-load without solar concentration using Freon in the bellows. As shown in Figure 5, tests were conducted using direct sunlight, the simple flat reflector, and water to cool the bellows at the bottom of the cycle. Stall torque and output power was insufficient to measure.

The test results in Figure 5 are averages of at least four measurements each with variations between measurements under identical conditions ranging as high as +150%, -80%.

Using the fresnel lens, more repeatable test results (variations within +30% under identical identical test conditions) were obtained and the average results are shown in Figure 6. As with the tests using air in the bellows, the performance was not significantly affected by angle of sunlight exposure (within +20°), or depth of water in the pan (beyond enough to wet the entire width of each bellows). It was affected by skew angle and sunlight concentration. The optimum half skew angle remains in the 5° to 6° region, however the higher concentration of sunlight (from 12 inch diameter to a 2 inch diameter spot) clearly produced higher performance (as contrasted with performance of the air bellows when the 5 inch spot produced slightly better performance). Figure 7 shows the same test results in graphical form.

Efficiency was successfully measured at the optimum conditions (Concentration to a 2 inch diameter spot and using a half skew angle of 6°) with reflected sunlight from overhead, water pan beneath, and a sunlight level of 90 mw per sq. cm. An average output torque of 6 ounce inches produced an average speed of 0.38 RPM, for an output of 0.0003 watts. Calculating the input power at 65.6 watts, the efficiency is 0.00045%.

Conclusions and Recommendations

The efficiency is extremely poor. The primary conclusion is that this type design is not suitable for prime power generation. The design should be optimized in another direction, specifically the advantages of simplicity (inherent reliability) and low cost must be optimized for those applications that do not require significant power.

Fig. 5(a) Test Set-Up

	No Water	With Water
Direct Sunlight	0.04	0.093
Direct + Reflected	0.073	0.17

Fig. 5(b) No Load Speed (RPM)
(Sunlight Intensity = 90 mw/cm^2)

FIGURE 5. Tests without Sunlight Concentration

Fig. 6 (a) Test Set-up

Half Skew Angle	4°	5°	6°	7°
Five Inch Spot:				
No Load RPM	0.57	0.65	0.50	
Stall Torque (oz. in.)	8.9	9.2	7.2	
Two Inch Spot:				
No Load RPM	0.63	0.76	0.79	0.67
Stall Torque (oz. in.)	7.0	12.0	11.8	10.0

Fig. 6 (b) No Load Speed and Stall Torque as a function of Axes Skew Angle and Solar Concentration (Sunlight Intensity = 90 mw/cm^2)

FIGURE 6. Test Data with Sunlight Concentration.

FIGURE 7. No Load Speed and Stall Torque as a function of Axes Skew Angle and Solar Concentration

During the course of the project two alternate bellows designs were considered but rejected for this engine design. One is the welded steel bellows which provides maximum stroke for any given diameter. The other is the Bellofram diaphragm cylinder which provides minimum friction/resistance to displacement. Although these are mentioned here for other investigators, they are not recommended for this type design due to their higher cost. However they may be well suited for use in more conventional push rod and crankshaft engine design aimed at higher efficiency.

However, with minimum cost, low spring rate and performance repeatability in mind this investigator does plan to proceed with the development of this engine using the deposited nickel bellows. Deposited nickel bellows are quite economical in small sizes (typically, 1 inch diameter) and have an attractive low spring rate due to their thin wall (manufactured by electrodepositing nickel on a mandrel core which is later chemically removed leaving the nickel bellows). While seeking high power these small bellows have been avoided. However, for the small low power, low cost market this type bellows is very appropriate. Regarding repeatability, a solution must be found for the assembly preload problem if Freon is to be used, and if service free life is expected. Due to the exceptional repeatability of the deposited nickel bellows, it appears feasible that a welded seal bellows assembly containing Freon could be produced which would be sufficiently balanced upon manufacture as to require no valves for rebalancing.

With minimum cost in mind, an attempt will be made to design the next engine with the axes held in the required skewed angle by two bearings, instead of four. Instead of creating a force couple on each axle with two bearings carrying a radial load each, a search will be made for an appropriate bearing designed for high thrust loads in either direction, so that a single bearing can transmit the skewing torque to the bellows end plates. This will reduce the parts count to bellows, Freon, end plates, a fixed, skewed axle and two bearings. Efforts to reduce the number of bellows must await solution of the assembly preload problem to be sure of the bellows design resulting from that solution.

Concurrent with the development of the engine, the identification of the market must proceed. Applications must be identified where simplicity and/or low cost are of paramount importance and the output power needs are minimal. Applications which immediately come to mind include those where no mechanical connection is made to the engine, the output being either visual, as in the rotating display or optical, as in tracking the sun with a solar reflector. Wind loads would have to be essentially non-existent. Rotational speeds would have to be in the 1 RPM range, although a smaller engine having lower thermal time constant will have a higher output speed than the engine tested in this project. Unfortunately the market search half of new product development requires at least as much creative ability and perseverance as the design half.

Appendix

Photos of Rotary Solar Engine Components

Photo No. 1. Solar Engine Components showing from left:
Fresnel Lens, Solar Engine (in front), Water Pan (in rear),
Solar Meter, Rigid Mounted Central Bellows and End Plates
which proved impractical.

Photo No. 2. Solar Engine with each axis skewed 6° .
Note adjust screw at rear (top of photo) used to set skew angle.
Note brake drum at right to measure output power.

Photo No. 3. Fresnel Lens used during tests.

Photo No. 4. Rigid mounted Central Bellows and End Plates which used spherical ball joints at each end of each power bellows (two shown in top position). This technique for mounting the bellows proved to have too much friction and was rejected (see text: Bellows Ends and Bellows Preload).

Photo No. 5. General Test Set-up. Adjustable Reflector overhead, on table: Water Pan in foreground, Solar Engine in middle, Freon tank in background.

Photo No. 6. Close-Up of Test Stand with table in shadow from afternoon sun but reflector (not in shadow) producing vertical sunlight upon solar engine. Note Water Pan in position for operation, under Solar Engine Rotor.