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Solar-powered Stirling engines: a low-cost possibility for village power, pumping and cooling

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Abstract: Stirling engines are heat engines that operate on a closed thermodynamic regenerative cycle and are used as power systems, refrigerators or heat pumps. Recent developments in Stirling technology allow the use of low temperature heat sources including flat plate solar collectors. New concepts for low-cost, low ΔT Stirling engines that may be made by village craftsmen using locally available materials are presented. It is anticipated that the machines will be used for water pumping, low capacity refrigerators for food and vaccine preservation, for air conditioning and for low level electric power generation (trickle charging an automobile battery to illuminate a 20/40 W bulb for a few hours during the dark hours).

Keywords: air conditioning, cleaner technology, low ΔT, power generation, refrigeration, solar power, Stirling cycle, water pumping.

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1 Introduction

Stirling engines operate on a closed regenerative thermodynamic cycle with compression and expansion of the same working fluid at different temperature levels. They may be used as power systems converting heat into work, as refrigerators for cooling and as heat pumps for elevating the temperature of heat drawn from an ambient temperature source. Both refrigerators and heat pumps require an input of work for their operation.

Stirling engines have a long history, dating from their initial development in the early years of the 19th century. The technology of Stirling engines has been well summarized by Walker *et al.*[1] Recent developments have resulted in Stirling machines able to operate on small temperature differences ΔT (less than 100°C) between the hot space and the cold space.[2,3] These developments allow the possibility to operate Stirling engines using flat-plate solar collectors, supplemented perhaps by a flat reflector to increase the solar flux incident on the collector. There is no need for the parabolic solar concentrators, absorbers and tracking systems used in conventional solar-powered Stirling systems. Such systems are considered to be economically infeasible for widespread use in developing countries.

Operation with low maximum cycle temperatures (less than 100 °C) eliminates the need for expensive machined parts (sometimes of relatively exotic materials). Instead low cost, locally available materials may be used, and the machines may be made by village craftsmen. Widespread use is anticipated of these low cost, low ΔT, 'low tech' engines for water pumping, for low capacity refrigeration for food and vaccine preservation, and for very low level electric power generation.

2 Solar power

Solar energy is incident on the Earth in prodigious quantities. Much of the energy is reflected, more is used by growing plants and vegetation, and ultimately sustains vegetarian and carnivorous animals. Still more is consumed to create weather systems (wind, evaporation, rain, etc.). Despite this, much of the solar energy is not used effectively. It is estimated that only 1% of the incident solar energy converted into electricity or mechanical work at an efficiency of 10% would provide more than all the energy presently generated by all the world's power stations and transportation systems.

The mean solar flux outside Earth's atmosphere is approximately 1460 W/m^2. Some of this is reflected and some is absorbed by the atmosphere, so the maximum solar radiation flux at sea-level is no more than 1,000 W/m^2 at the Equator at noon under clear sky conditions.

Using flat-plate collectors with a transparent glass or plastic top plate, it is possible to transmit to the collector about 80% of the energy (800 W/m^2) and to achieve an internal temperature of about 100°C. The use of a simple flat reflector will increase the energy incident on the flat-plate collector, the energy transmitted and the maximum temperature. The flat reflector may be a silvered glass mirror or simple aluminium foil on a flat sheet of card, plastic or plywood. It should be no larger than the flat-plate collector and at best will provide about a 40% boost in the transmitted energy and maximum temperature, i.e. to approximately 1100 W and 140 °C, respectively.

The maximum possible thermodynamic efficiency for conversion of thermal energy into work is the Carnot value, given by

$$\eta_{\text{th}} = \frac{T_{\max} - T_{\min}}{T_{\max}}$$

where η_{th} is thermal efficiency, $T_{\max}$ is the maximum cycle temperature (absolute, say $140 + 273 = 400$ K approximately), $T_{\min}$ is the minimum cycle temperature, the ambient temperature (absolute, say $35 + 273 = 300$ K approximately). Therefore

$$\eta_{\text{th}} = \frac{400 - 300}{400} = 25\%$$

Stirling engines routinely achieve thermal efficiences equal to half the Carnot value, i.e.

12.5%, but to be conservative let a value of 10% be assumed. This allows an estimate of the power (work) that might be obtained from a low ΔT Stirling engine with a 1 m^2 solar collector of 1100 W × 10% = 100 W approximately.

This is the power available under the best conditions at noon. The power level would be very approximately sinusoidal over the sunlit hours. A mean solar power level of 75 W for 5 or so hours a day might be feasible.

A good deal of water can be pumped per day with a power of 75 W for 5 or 6 hours. Similarly, a simple electro-magnetic charger and automobile battery would allow the use of one or two 25–40 W electric light bulbs for 3–4 hours per night.

Another possibility is to use the power produced by the solar-powered Stirling engine to drive another Stirling engine acting as a refrigerator. Such an arrangement is called a Stirling–Stirling or hybrid-Stirling unit.

Refrigerator operation is characterized by the coefficient of performance, which is somewhat similar to the inverse of the thermal efficiency. Between given temperature limits T_{ref} and T_{min}, the highest possible coefficient of performance is the Carnot value:

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{\text{heat lifted}}{\text{work input}} = \frac{T_{ref} - T_{min}}{T_{ref}}$$

where $\mathrm{COP}_{\mathrm{Carnot}}$ is the Carnot coefficient of performance, heat lifted is the refrigeration effect, work input is the work required to operate the engine, T_{ref} is the temperature at which the refrigeration is produced (say 0 °C, or 273 K), and T_{min} is the ambient atmospheric temperatures (say 308 K). Then

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{308 - 273}{308} = 7.8$$

Stirling refrigerators routinely achieve 40% of the Carnot value[4] so that the actual coefficient of performance is 7.8 × 0.4 = 3.12, say 3. A mean power input of 75 W for 5 hours would provide refrigeration capacity of 225 W for 5 hours (1.125 kWh) of cooling at a temperature of 0 °C. This relatively small amount of refrigeration (trivial by customary refrigeration and air conditioning practice) is quite sufficient to cool medicines, and perishable foods in a well insulated (Styrofoam) cabinet or to provide some personal comfort and relief if used in an elementary air conditioning system.

3. Low ΔT Stirling engines

Various concepts for low ΔT Stirling engines to fulfil the above requirements have been investigated and their validity confirmed. Some that appear most applicable are briefly described below.

The preliminary experimental work was carried out using small model engines. This allows concepts to be rapidly evaluated at little cost and requires no extensive infrastructure or facilities.

The model engine used for most of the experimental work was the Ringbom–Stirling engine shown in Figure 1. The engine was designed by Professor James Senft (Department of Mathematics and Computer Science, University of Wisconsin, River Falls, WI, USA) in the course of his continuing study of low ΔT Stirling engines. It is manufactured by the New Engine Co. Ltd (12121 NE 66 St. Kirkland, Washington

98933, USA). Ringbom-Stirling engines are characterized by the use of a free displacer and a crank-controlled piston. The technology for Ringbom-Stirling engines has been well summarized by Senft.[3] The engine shown in Figure 1 is designed to operate with hot water in the reservoir or well in which the engine is starting. It runs for several hours on a litre or so of hot water. In this orientation the bottom plate of the displacer cylinder is the hot plate (as hot water temperature) and the upper plate is the cold plate (at room temperature). It is this temperature difference between the two plates that causes the engine to run. Heat is drawn from the hot water through the hot plate to the air inside. Heat is ejected from the air through the top plate to the environment. Some of the heat entering the engine is converted into work to drive the piston-crank-flywheel assembly.

Of course, with a solar energy input the hot plate would be the top plate and the cold, air-cooled plate would be underneath. This can be achieved by inverting the engine. It was observed to operate just as well in this orientation as in the normal case.

Early in the development programme it was found that substantial improvement in performance, and great simplification in manufacture, could be gained by converting this machine into the free piston arrangement shown in Figure 2. Free piston Stirling engines are another special class of Stirling engine, in which there are no kinematic mechanisms connecting the piston and displacer to each other or to the crankshaft-flywheel assembly. In a free piston Stirling engine there is no crankshaft or flywheel. The output work is taken directly from the piston to drive a linear electric generator, a water pump or gas compressor. The technology of free piston Stirling engines has been well summarized by Walker *et al.*[6]

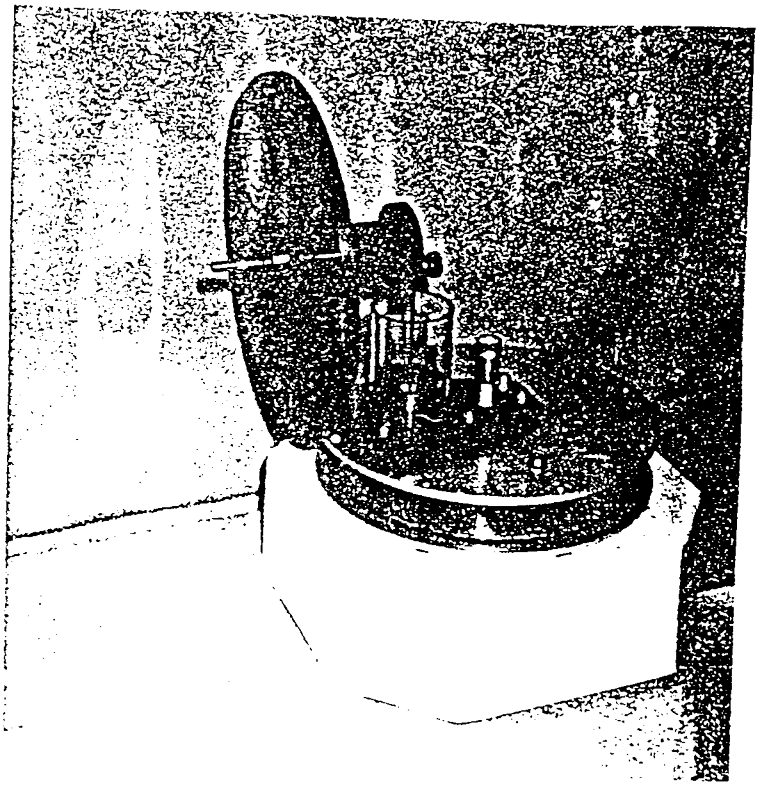

Figure 1 Low ΔT Ringbom-Stirling engine.

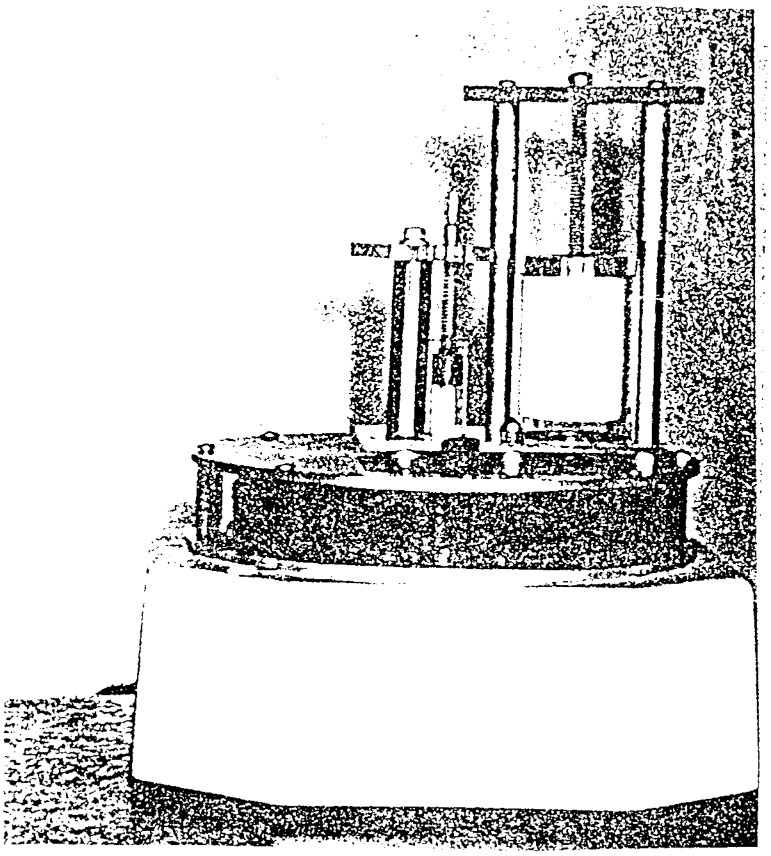

Figure 2 Low ΔT free-piston Stirling engine.

In the free piston version of the Senft machine shown in Figure 2, both the displacer and the piston when at rest are held in the midstroke position by light coil springs. The springs are provided simply to support the reciprocating elements in the rest position and facilitate easy starting. They play little or no part in the operation of the engine when it is running. Free piston Stirling engines operate at their natural resonant frequency and are essentially a tuned fluid circuit. Both the piston and the displacer oscillate at the same frequency, the displacer leading the piston by about one-quarter cycle. When the load conditions or temperature regime change the frequency remains the same but the stroke (principally of the piston) changes to reflect the increase or decrease of work output.

Free piston Stirling engines may be used as power systems or refrigerators. In power systems, work is taken directly from the reciprocating piston to operate the plunger of a water pump or air compressor. The piston may also cause the oscillation of the armature or the 'stator' of a linear electromagnetic power generator. Permanent magnets may be used for small power systems, and it is nearly always most convenient for the magnets to be located (and oscillating with) the piston while the static conductor coil is arranged in an annular doughnut-shaped assembly around the piston and cylinder in which it is oscillating.

When Stirling machines are used for refrigeration various arrangements are possible. With electric power available the driver may be a linear electric motor similar to the electromagnetic generator described above. Power input to the conductor coil creates a magnetic field, which interacts with the permanent magnets on the piston to create a linear driving force causing the piston to move.

When thermal (solar) power is to be used to energize the refrigerator, the arrangement shown in Figure 3 may be used. Here, a solar-powered Stirling engine produces work to drive the Stirling refrigerator. Various mechanical arrangements for this Stirling–Stirling combination are possible. An attractive arrangement shown in Figure 4 combines two displacers, one for the power system, one for the refrigerator with a common piston. Early experimental work has been carried out with the version of the common piston Stirling–Stirling arrangement shown in Figure 5.

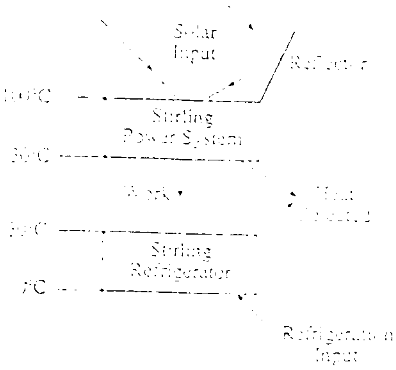

Figure 3 Heat activated Stirling–Stirling refrigerator.

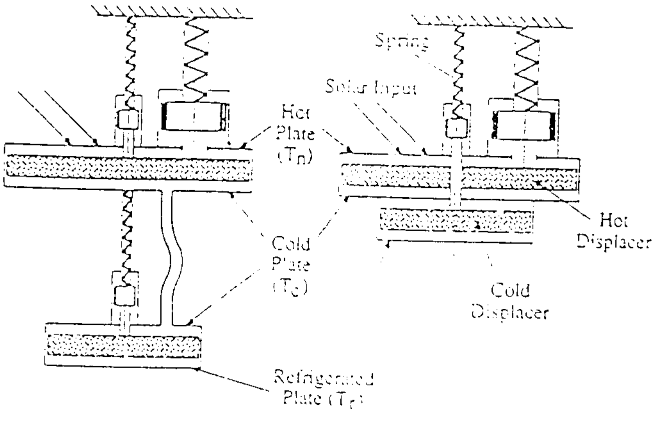

Figure 4 Solar-heated Stirling–Stirling refrigerator with common piston (alternative arrangements).

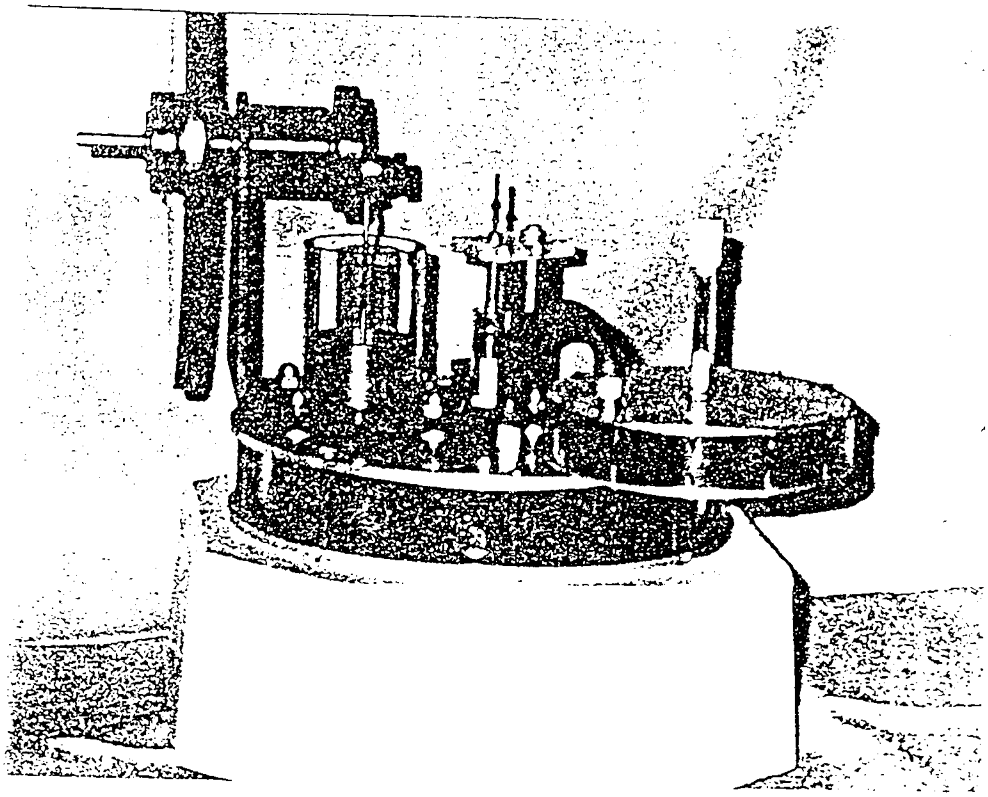

Figure 5 Heat-activated Stirling refrigerator.

4 Self-starting systems

For solar-powered Stirling engines, a self-starting device able to start the engine with no human intervention is clearly desirable. The self-start system should activate automatically when the conditions are suitable to accomplish a start. In solar-powered engine this is clearly at a suitable interval following sunrise when the Sun has ascended high enough for the incident solar energy in the engine to warm the top plate solar collector to the necessary minimum temperature.

It is also highly desirable for the starting device to (i) become disengaged and to remove itself from the oscillating parts during normal operation, and (ii) have the capability to reset itself in the 'start' position at sunset or when clouds obscure the Sun so the engine cools below operating temperatures.

Given these requirements it is likely that the starting system will be thermally activated, depending on the incident solar flux to trigger the 'start' and removal procedure, and for an absence of solar radiation to cause a reset procedure.

Free piston Stirling engines may be started very easily simply by disturbing the static equilibrium of the piston and displacer. The slightest movement will cause the assembly to rapidly (almost instantly) take up its cyclic operation at the resonant frequency.

Separate support springs for the piston and displacer are provided in the machine shown in Figure 2. These springs hold both elements in the static rest position at the approximate mid-point of their stroke. Starting is accomplished simply by disturbing the displacer (or piston) slightly from the rest position (in either an upward or a downward direction).

For the engine shown in Figure 2 an effective automatic self-start and reset system was devised. The self-start system is not shown in the Figure 2 pending a patent application. Basically, it depends for its operation on the inflation of a bladder when heated by the sun to cause the necessary disturbance to the equilibrium of the displacer.

5 Prototype solar-powered Stirling engine

Figures 6 and 7 show a prototype solar-powered Stirling engine called the Erector, which incorporates the principles discussed above. This is believed to have great development potential for use in the village power applications described earlier. The Erector is amazingly simple in its construction. It consists of a shallow plastic dish of large diameter (40 cm) available at low cost in garden supply stores for use as the saucer for large flowerpots.

The top is covered by a sheet of thin transparent acetate sheet (Perspex™ or Lucite™). The piston and cylinder assembly is mounted on this sheet with the space below the piston in direct communication with the volume of the dish through a large port in the top plate. The piston is held by a spring in the rest position at the mid-point of the stroke.

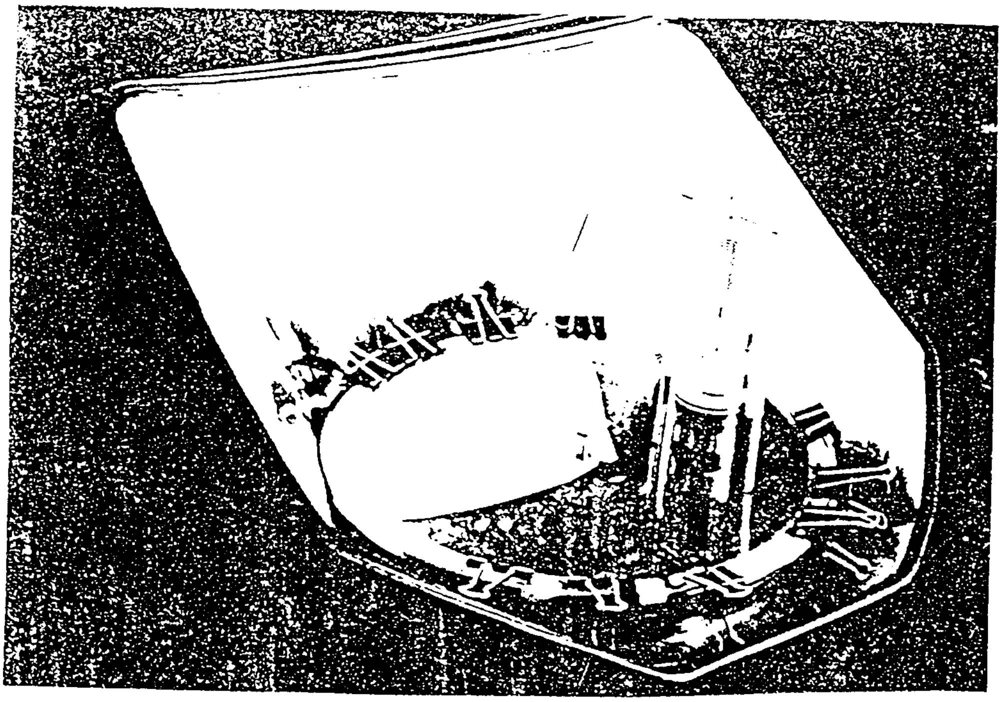

Figure 6 Solar-powered Stirling engine.

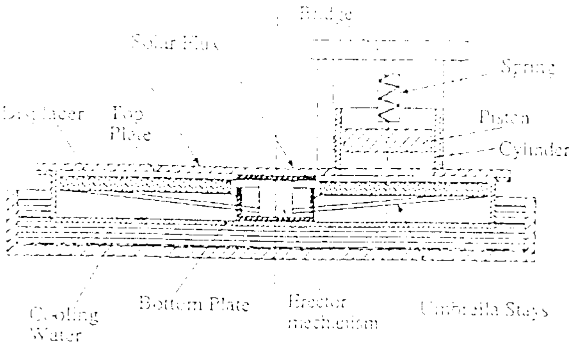

Figure 7 Erector solar-powered Stirling engine.

The displacer is a sheet of porous plastic material with a very low mass. This may be had in several porosites and thicknesses. It is very low in cost, and fits loosely in the shallow plastic dish. It is activated by several thin wire levers arranged in radial fashion from the central driver, somewhat reminiscent of an umbrella frame.

When the engine is in operation the pressure of the air enclosed in the system fluctuates cyclically. This variation in pressure causes the thin plastic top plate and bottom plate to flex as diaphragms. The flexing action of the top and bottom plates acts on the central driver, alternately squeezing it when the plates come together at low pressure and releasing it when the pressure is high, causing them to flex apart.

The alternating squeezing and releasing in the central driver causes the thin wire radial levers to rise (when the pressure is low) and to fall under gravity when the pressure is high and the squeezing of the driver is released. The rise and fall of the radial levers cause the displacer to oscillate in the displacer dish, driving the air inside the dish from the hot space above the displacer (heated by the Sun) to the cold (water-cooled) space below the displacer. The change in temperature of the air due to the motion of the displacer is the effect that causes the pressure fluctuations that drive the engine.

The same cyclic pressure change acts on the underside of the piston while the topside of the piston remains exposed to the atmospheric pressure. Thus when the pressure in the engine is above atmospheric the piston rises, and it falls when the pressure in the engine is below atmospheric. The piston is a relatively heavy mass of material so, when it moves, there are significant inertia effects that carry the piston both higher and lower than the points at which the system pressure is exactly the same as the atmospheric pressure. As a consequence of the inertia effects the motion of the piston causes some partial compression and expansion of the working fluid (air) in the system, thereby increasing the amplitude of the pressure fluctuation and causing the motion of the displacer and the piston.

In this machine the solar energy enters the engine through the transparent top plate. The piston and cylinder assembly could be arranged in a variety of ways; through the top case as shown in Figure 6, through the bottom plate, or as a separate assembly coupled by a transfer tube to the displacer cylinder.

It has been found the system operates best when the piston is an easy loose fit in the cylinder with considerable 'blow-by' of working fluid past the piston, exiting when the piston is rising and the system pressure is high, entering when the piston is falling and the pressure is low. This is an important fortuitous characteristic of the engine because it substantially relaxes the requirements for the piston and cylinder combination. There is no need for a precision fit of the piston in the cylinder. Instead the cylinder may be made of a low cost item, say a glass bottle with top and bottom cut off using the well known wire and hot oil technique. The cylinders of larger engines may be made from the circular plastic oil and chemical drums found in abundance throughout the world, including the developing countries. The piston can be a similarly simple volume, another glass bottle or metal or plastic container, full of water.

6 Working fluid

For high-performance, dense-power Stirling engines it is necessary to use the light gas working fluids hydrogen or helium. This allows the engine to run at high speed (60–70 Hz) and high pressure (200 atm) to achieve power densities equivalent to those of the internal combustion engine. For the village solar-power engines (low speed, 10 Hz, low power) described in this paper the use of hydrogen or helium working fluids offers no thermodynamic advantage over air. Air has many advantages, however, the greatest of which is that it is abundantly available at no cost throughout the world.

The power output of the Stirling engine increases with increase in the pressure of the working fluid. There is considerable benefit to be gained by increasing the pressure level of air in the engine by means of a small pump: a bicycle pump, an automobile tyre foot pump or a simple bellows type compressor driven by the Stirling engine. Such pressurization of the engine is very worthwhile for small Stirling engines heated by biomass combustion. It is less applicable for the low ΔT solar-powered Stirling engines. The low solar input flux makes acquisition of the solar energy the principal limitation of the class of machine operating without an (expensive) concentrator. There is therefore little to be gained by introducing the complexities of pressurization to gain the advantage of a small engine.

7 Conclusion

The first phase of development, to investigate and prove some low ΔT solar-powered Stirling concepts, has been accomplished. Subsequent efforts will be directed to the design and development of full size (1 m^2 collector) prototype engines.

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