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A Free Cylinder Stirling Engine Solar Powered Water Pump

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SUMMARY

This paper describes a free cylinder Stirling engine expressly designed for use as a solar water pump. The pumping action takes place as a result of the reciprocating motion of the cylinder of the sealed free piston engine, this cylinder motion being used to directly drive a reciprocating water pump.

A 250 watt unit is described, comprised of a free cylinder engine, a faceted focusing collector containing many small mirrors, an equitorial mount, clock drive, tracker and tensioned cable pump. Expected cost of a complete system delivering 250 watts to the water (25 liter-meters/sec) is about $500 in large scale production.

INTRODUCTION

Shortly after the author began work on the free piston Stirling Engine in early 1964, an attempt was made to build a simple single piston free piston Stirling Engine, using air at atmospheric pressure as its working fluid. This first attempt proved unsuccessful because the very low power produced by the cycle was inadequate to overcome the frictional and other losses in the crude mechanism used. The engine was then sealed and pressurized, with the intent of producing work by pumping gas around a closed pressurized loop. This scheme succeeded but no power was delivered outside the system. But in the course of these experiments it was noticed that the moving cylinder of the unbalanced single piston engine was itself capable of significant work, so a simple water pumper was built comprised of a tube shape free cylinder engine directly acting on a column of water in which it was immersed. The flowing water was used to cool the engine as well as to absorb power from it. This concept was described in Ref. 1.

Shortly afterwards a more serious attempt was made to make a solar powered water pump based on a free cylinder engine, which resulted in the successful operation of an entire system-Fresnel lens, engine, pump, polar mount and tracker. This was described in Ref. 2 and was displayed at the 1971 Solar Energy Society meeting at the Goddard NASA laboratories.

Since no sponsors were found to fund further development, this promising concept lay unexploited until 1979, when the Sunpower team again undertook to apply their by then large accumulated experience in design, analysis, and construction of free piston Stirling engines to the problem of Solar water pumping. As a start, one of the older Sunpower designs, the Model 10, was modified to operate as a free cylinder engine, and with the investment of less than one man week of time, the Model 10 water pumper was working in a very satisfactory way, delivering about five watts of pumped water. (Fig.1) The power output of the same engine with an alternator load had been about 20 watts. The reduction in power in the free cylinder mode was due to the reduced pump frequency and to pump inefficiency, the pump being a simple, quickly built one not optimized for its task.

With this encouragement, it was decided to undertake the next step--modification of the newer Sunpower Model 100 alternator engine to a free cylinder water pump configuration.

The Model 100 had demonstrated excellent performance, producting about 70 watts of electric power from an alternator of about 70% efficiency. (Ref. 3) In the water pump form it would run slower, but would nevertheless be potentially capable of about 70 watts delivered to the water pump, which in turn was expected to produce about 50 watts (5 liter-meter/sec) of pumped water. This project is underway at the writing of this paper.

During the modification of the existing

machine, a concept evolved which is believed to represent a superior Solar water pump system. The rest of the paper will describe the reasoning behind the concept, the characteristics of its components and its expected performance, cost, and use.

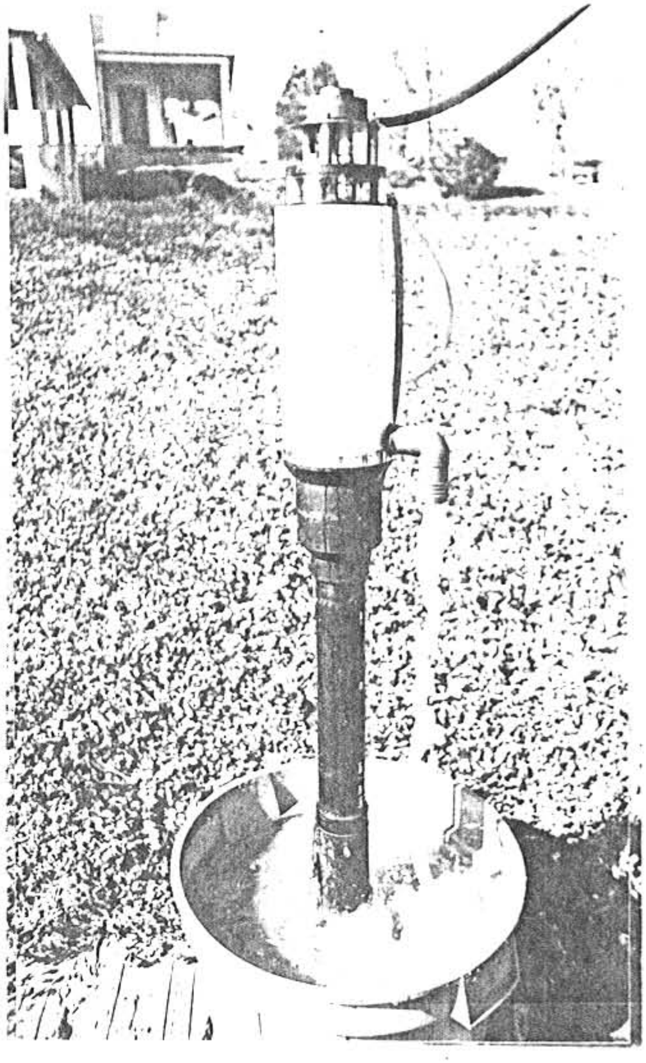

Fig. 1 Model 10 Water Pump

RATIONALE FOR PROPOSED CONCEPT

There is no doubt that the world could use a practical solar powered water pump. Study after study has shown that in the developing nations water of adequate quality and quantity is scarce, and human health and agricultural productivity suffer as a result. Fuel to drive conventional water pumps is scarce and expensive and growing more so, but sunlight is often abundant. Many attemps have been made to make solar powered water pumps, almost all using various forms of the Rankine cycle with water or organic working fluids and large low temperature collectors. System efficiency has been very low, on the order of a few percent, and cost, largely due to the extensive collector area required, has been high. Silicon solar cell systems also suffer from high cost and low overall efficiency--no more than about 4% can be expected from the cell - motor - pump combination, which means that costs per watt of hydraulic power delivered must be in the range of $15 even with $3/pw solar cell panels.

While Stirling engines promise high efficiency, conventional crank drive Stirling engines have problems with both gas leakage out and lubricant leadage in to the working spaces, neither of which can be tolerated. And if low pressure air engines are used, their size is excessive for the power and their efficiency is low. The seal and size problem is avoided in the free cylinder Stirling engine which is extremely simple, hermetically sealed and has no lubricant other than the working gas. Its thermal efficiency is at least as good as the best crank driven Stirling and usually better, since there is no bearing and seal drag to reduce mechanical efficiency.

The free cylinder Stirling Engine is well adapted to use in dusty or otherwise hostile environments since its accurately fit components, the piston and displacer, are completely sealed within the pressure vessel and cannot be affected by outside influences.

The power output of the free cylinder engine is derived from the oscillatory motion of the sealed pressure vessel, and can be used to pump water in a variety of ways--directly, by use of a pump plunger directly attached to the cylinder, as in Fig. 1, or by remote attachments via a cable, rod, hydraulic line or even an electric generator. Since simplicity, ruggedness, low cost and efficiency were the requirements set for this design, a mechanical drive was chosen.

The collector may be made of multiple facets of glass and is simple, rugged, relatively low in wind profile, and quite adaptable to local manufacture, as is everything about the system.

The optical quality and tracking accuracy of the collector, and the absorber efficiency, are the major determinants of the system efficiency and cost, but even with simple tracking systems such as a gravity driven escapement or a spring wound clock, and with multiple faceted hand placed mirrors, the system performance can be expected to be acceptable.

Table 1 summarizes the proposed system shown in Fig. 2, characteristics of which are discussed in more detail below.

Table 1

Engine	Power Output	- 315W
	Length	- 35cm
	Diameter	- 6cm
	Stroke	- 2cm
	Pressure	- 20 bar air or nitrogen
	Efficiency	- 28% @ 650C
	Frequency	- 25hz
	Cost	- 80$
Collector	Area	- $2.88M^2$
	Surface	- Second Surface Glass
	Cost	- 200$
	Efficiency	- 75%
Absorber	Type	- Cavity
	Efficiency	- 70%
	Cost	- 15$
Tracker	Type	- Polar-single axis
	Drive	- DC Motor + Solar Cell + Clock + Sun Seeking Collector
	Cost	- 30$
Pump & Drive	Type	- Direct Induction Low Head
	Efficiency	- 70%
	Cost	- 15$
	Type	- Sprag Clutch High Head
	Efficiency	- 70%
	Cost	- 35$
Mount	Cost	- 80$
System	Efficiency	- 13% - 11%
	Cost	- <500$ In Large Scale Production (>10,000/year) ~2$/Watt delivered to water.
	Power to Water	- 250 Watts at $800W/M^2$ insolation

DETAILED DESCRIPTION OF SYSTEM

Engine

The engine is comprised of a displacer, a piston and cylinder containing the heater, cooler, and regenerator for the Stirling cycle. The displacer is driven by the gas forces acting on the displacer rod, and is sprung to the piston. (Ref. 4 gives a description of the logic behind the free piston engine design.) Dynamic interactions between the three components are optimized by the methods described in Ref. 5 for a temperature range appropriate to the collector and absorber. This appropriate temperature depends on the local insolation, and the quality of the collector and the accuracy of the tracking method used, and ranges downward form about 1000K, the temperature we have found to be optimum for very refined optical systems and cavity absorber coupled to a Stirling engine. Internal components are closely fit but do not require any contact seals such as conventional piston rings. Sliding surfaces are hard surfaced and lubricated with teflon based solid lubricants and by gas bearings. Diametral clearances between piston and cylinder are about 0.02 mm in a 50 mm bore.

The power absorbed by sliding friction is a trivial fraction of engine power. In measurements made on a 1 kW engine, there was less than 1% difference between gas power and power delivered to the load.

The engine responds to varying load forces by changing stroke and frequency. Light loads permit high frequency and long strokes and heavy loads result in shorter strokes and lower frequency. This permits ready accomodation to a varying head of water in the pump.

Self starting is assured by the methods described in Ref. 6. Only the establishment of a temperature difference is necessary to cause the engine to begin its oscillation.

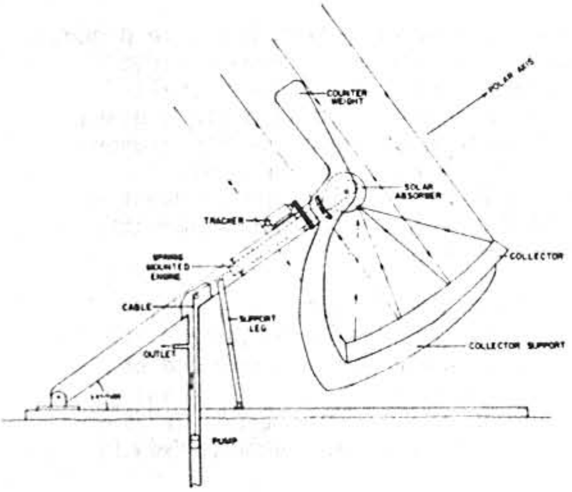

Fig. 2 Proposed Solar Water Pump System

Power Transmission System

Fig. 2 shows the power transmission system for a shallow well pump. The oscillation of the engine is directly transmitted to the piston of the induction pump (Ref. 8) via a tensioned cable and pulleys. This method is efficient, simple and easily repaired. The induction pump is a well developed and efficient device able to handle dirt or sand laden water.

Fig. 3 shows a sprag clutch drive comprised of a first sprag clutch (infinite division ratchet) driven by the engine oscillation, a second sprag clutch preventing recoil of the torsion tube, a torsion tube which serves to store pulsating energy from the engine and deliver smoothed torque to the crank, connecting rod and slowly oscillating deep well pump. By this simple mechanism, the high frequency short stroke engine oscillations can be connected to the high torque, slow rotation and reciprocation appropriate for a deep well.

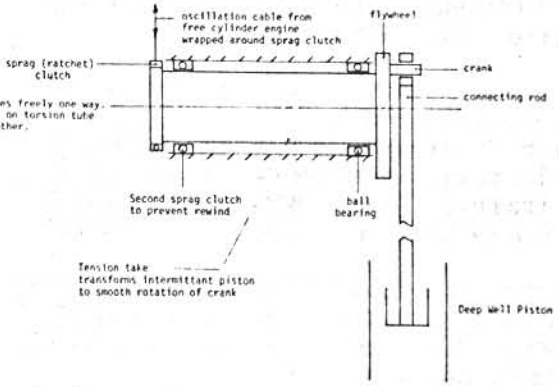

Fig. 3 Sprag Clutch Drive

Collector

The collector can be made from a single piece, or from several segments, of from a large number of small mirrors each individually aimed at the absorber. Second surface glass is the most promising because of its proven durability and high performance. Glass weight is a problem but the type of mount chosen is strong and stiff and can handle glass mirrors well.

Where hand labor is abundant, local manufacturesrs could make the small mirror collectors using a backup support of wood or sheet material of whatever type is readily available. Each small mirror could be imbedded in epoxy or other suitable matrix.

COMPARISON OF PROPOSED SYSTEM WITH ALTERNATIVES.

The proposed system has several very significant advantages over alternate solar powered water pumps already funded: its relatively high overall system efficiency, its low level of technical risk and its low cost per unit of water delivered. The following paragraphs will amplify these claims.

In comparison with the photocell system, the free cylinder Stirling is more than twice as efficient, and potentially less than 1/3 the cost. None of its components have the intrinsically difficult, high cost character of the silicon Solar cell and all have well understood paths to improvement. But even with the present efficiencies previously described, the proposed system is far ahead.

A good comparison of the Rankine System state of art is made available in Ref.7, in which only 3% overall efficiency was recorded at a cost of 15$/Watt of water power delivered under the best conditions of solar intensity for a large (37 kW) system. This compares with over 10% system efficiency and less than 2.5 $/Watt for the developed Stirling System.

Most other potential Solar water pump systems, liquid piston, atmospheric air engines,etc., have efficiencies below 1% and developmental difficulties of high order.

In contrast to the others, the free cylinder system has demonstrated feasibility in three generations of working prototypes, and even in its earliest crude embodiment showed about 3% system efficiency (power to water/Solar energy incident on collector), equal to that of the refined Rankine System of Ref. 7.

Another advantage is the possibility of connecting a large number of relatively small engine-collectors together on a common sprag clutch driven shaft to get high power for a single deep well. This strategy is dictated by the well known fact that accurate concentrator surfaces reach a minimum cost/kW at relatively small sizes on the order of a few kW, so that large power is best achieved by grouping of smaller units. It should be noted that the identical system may be immediately operated on a burner (biogas or the like) by simply slipping off the solar absorber and replacing it with a burner-recuperator. It is even possible to combine the burner with the absorber so that no hardware change need be made to switch form one heat source to the other.

Table 2 gives an approximate cost comparison between Stirling, Rankine and photovoltaic Systems taken from various papers in Ref. 7.

Table 2

COMPARISON OF SYSTEMS $\$/WATT$ OF PUMPED WATER
PER SQUARE METER OF COLLECTOR

Stirling Free Cylinder 600C Hot End				Rankine (Ref.7) 350C Hot End				Photovoltaic 3$\$$/PW Photocells			
Component	Eff.	Power Out/M^2	$\$/M^2$	Component	Eff.	Power Out/M^2	$\$/M^2$	Component	Eff.	Power Out/M^2	$\$/M^2$
Collector	.7	450	50	Collector	.7	450	50	Photocells	.1	100	300
Absorber	.7	313	5	Absorber	.7	313	5	Motor	.6	60	30
Engine	.25	78	30	Engine + Thermo Cycle	.10	31	40	Pump	.6	36	5
Mount & Tracker	--	--	20	Mount & Tracker	--	--	20	Auxiliaries	--	--	15
Pump	.6	47	5	Pump	.6	18	5				
Net Power to Water	--	47W/M^2	--	Net Power to Water	--	18 W/M^2	--	Net Power to Water	--	36 W/M^2	--
System Cost	--	--	110 $\$/M^2$	System Cost	--	--	120 $\$/M^2$	System Cost	--	--	350 $\$/M^2$
			2.55 $\$$/Watt				6.67 $\$$/Watt				9.8 $\$$/Watt
Relative Cost,$\$$/Watt	--	--	1	Relative Cost,$\$$/Watt	--	--	2.6	Relative Cost,$\$$/Watt	--	--	3.64

CONCLUSION

The free cylinder Stirling Solar Water Pump System described here has potential for low cost, durability and largely local manufacture. It is imminently suited for development as a practical solar water pump in both small and large sizes.

ACKNOWLEDGEMENT

As is always the case at Sunpower, everyone had a hand in the development of the concepts discussed here. In particular the contributions of Charles Rankin, Bruce Chagnot and David Gedeon are gratefully acknowledged.

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