DUPLEX STIRLING MACHINES

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ABSTRACT

The duplex Stirling concept - in which a Stirling engine drives a Stirling cycle heat pump - presents a major technological advantage over other types of heat pumps. The free-piston free-displacer device has nominally three moving parts in a single pressure enclosure, the same working fluid in both the engine and heat pump sections, freedom from halogenated hydrocarbons, all this in a highly efficient, well matched system. Over the past five years Sunpower has successfully developed and demonstrated various forms of duplex Stirling devices, ranging from gas fired refrigerator systems having 50W capacity to a residential heat pump having a 10kW capacity. This paper describes some of these projects, and presents an update of this new and very promising technology.

INTRODUCTION

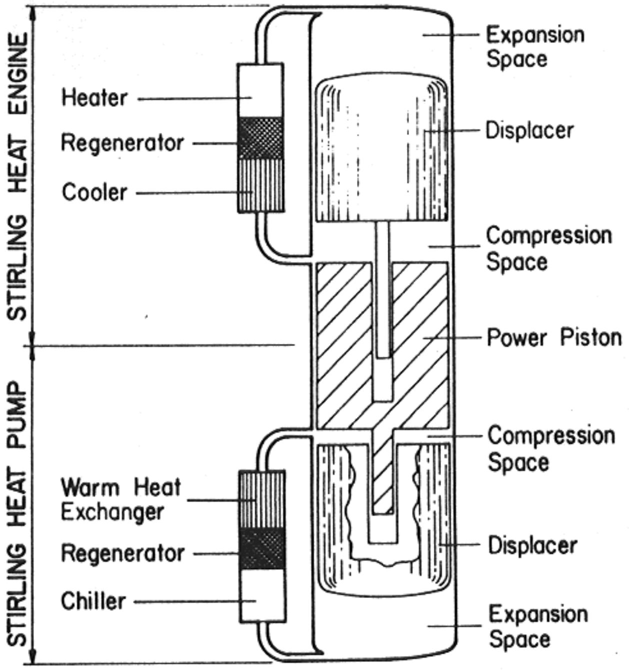
The free-piston Stirling engine is a potentially high efficiency, quiet, and high reliability device. The duplex Stirling heat driven heat pump is essentially two free-piston Stirling machines sharing a common piston and pressure enclosure. One working pair of displacer and piston operates as a heat engine, driving the other pair in the same pressure envelope which then operates as a heat pump (Figure 1). In both halves the displacer receives its driving force from a differential area between expansion and compression spaces embodied on the displacer rod. The uniqueness of the design is that the two Stirling machines are served by a common piston resulting in a configuration having only three moving components. When high temperature heat is applied to its heater, the heat engine section produces mechanical energy which is used by the heat pump section to pump heat from the cold source to the warmer sink. The resulting three element system is a potentially effective, simple and durable heat driven heat pump, including all the advantages normally associated with free-piston Stirling engines.

The duplex free-piston Stirling engine concept originated early in the history of free-piston engines (1). Actual hardware coolers and heat pumps have been built at Sunpower and demonstrated throughout the world since 1979. This paper describes three hardware projects at Sunpower covering a large spectrum of related duplex Stirling technology, including a natural gas liquifier, a residential size heating heat pump and a portable refrigerator demonstration unit.

NATURAL GAS LIQUIFIER

The natural gas liquifier represented the first program at Sunpower to specifically apply the duplex concept to a system of much larger size than the laboratory demonstrators produced up to that time. Economic analysis indicated that such a system could make use of gas produced in marginal wells converting it into useful fuel for transportation equipment at prices well below that of gasoline or diesel fuel. Other attractive applications included use at homes or small vehicle fleet operators for the production of transportation fuel from the existing natural gas supply.

Fig. 1 Duplex Stirling Machine



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The basic design of the natural gas liquifier has been previously presented (2), thus the remainder of this review is directed to actual hardware developed and testing accomplished. Figure 2 shows the assembled liquifier (minus the burner) made up of a 2.5 kW heat engine and a cooling machine designed to lift approximately 500W at 110K. The engine portion of the system employed the same basic engine used in the heat pump program and was tested on a heat pump simulator prior to being run with the liquifier in the duplex mode.

During the test phase the engine encountered a number of development problems primarily concerned with operating stability and lower than expected output. These problems were eventually overcome with the engine power exceeding the necessary 2.5kW and all the stability goals met. However considerable program slippage had occured during this time period.

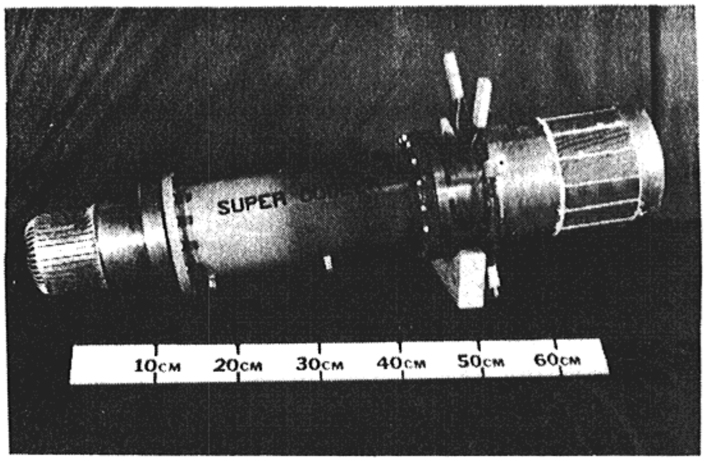


Fig. 2 Natural Gas Liquifier

Initial full duplex operation of the system proved unsuccessful in that only low power operation was possible. On attempting to increase power the system became unstable. Analysis indicated the most probable cause was power matching between the engine and heat pump. While it was initially thought that a system of this size could be run without an active control system these test results indicated that one would probably be required.

Due to program termination at this point, the duplex system testing ended without reaching the power levels required to truly evaluate the overall system performance.

In an attempt to characterize the Stirling cooler design, a brief inhouse program was undertaken to electrically drive the cooler. The primary goals were to investigate the dynamics of the cooler displacer and steady state performance at temperatures approaching those required for natural gas liquification. During testing a number of displacer gas spring and centering arrangements were also investigated. A total of 8.4 hours of steady state operation, with temperatures down to approximately 150K, was accomplished during this program. Individual tests were limited to less than one hour due to wear on the crank linkage shaft seal causing excessive leakage.

Conclusion

While the natural gas liquifier did not reach its design goals, considerable information on duplex Stirling system operating characteristics, Stirling cooler performance, and a clear understanding of the necessary modifications for further development of this concept were acquired. It is important to note that the results of other Sunpower duplex programs are also directly applicable to any future natural gas liquifier efforts, particularly those concerning cold end displacer control developed in the residential heat pump program.

RESIDENTIAL HEAT PUMP

This project represented an initial investigation of the duplex Stirling heat pump concept and its applicability to the residential sized (10K to load) heat pump market (3). The primary goal was to categorize the Stirling heat pump sub-assembly and determine the potential operating system COP of this concept in a heating-only mode. Other areas of critical importance such as heat-engine heat pump matching, regenerator and heat exchanger design concepts, and system arrangements were also investigated so as to build a solid technology base for further development of this concept.

Early in the program it was felt that sufficient differences existed between the proposed heat pump and any previously tested Sunpower machine to warrant the construction of a test rig of the Stirling heat pump before committing to a final design. A 1/10 scaled crank driven heat pump test rig was built and tested (Figure 3). The test rig did indicate that the projected COP of 1.5 for the total duplex Stirling heat pump system could be achieved.

Results from the test rig were used to review and modify the full size heat pump design. The heat exchanger design evolved from a flat plate arrangement with the regenerator sandwiched between them to an arrangement of a finned spiral tube coil housed within the pressure vessel in an axi-symmetric wrapping about the displacer cylinder (Figure 4). The regenerator was thickened to reduce the conduction losses and sandwiched directly between the two heat exchangers. The revised design was believed superior to the previous one both fluid-dynamically and from the fabrication point of view.

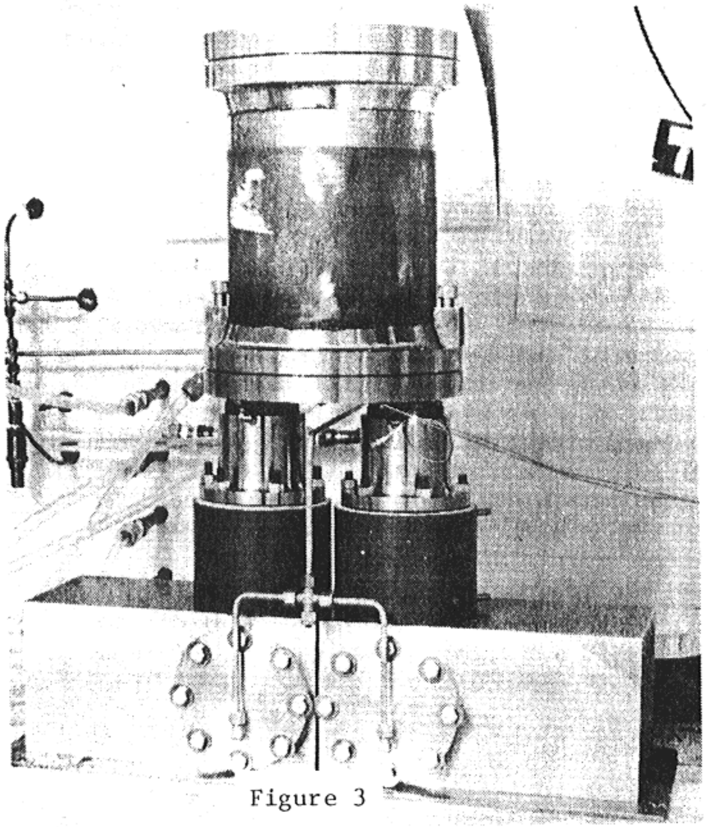


Figure 3

The overall heat pump design was as conservative as possible postponing questions of cost and fabrication difficulty until the thermodynamics of the low temperature Stirling cycle had been proven.

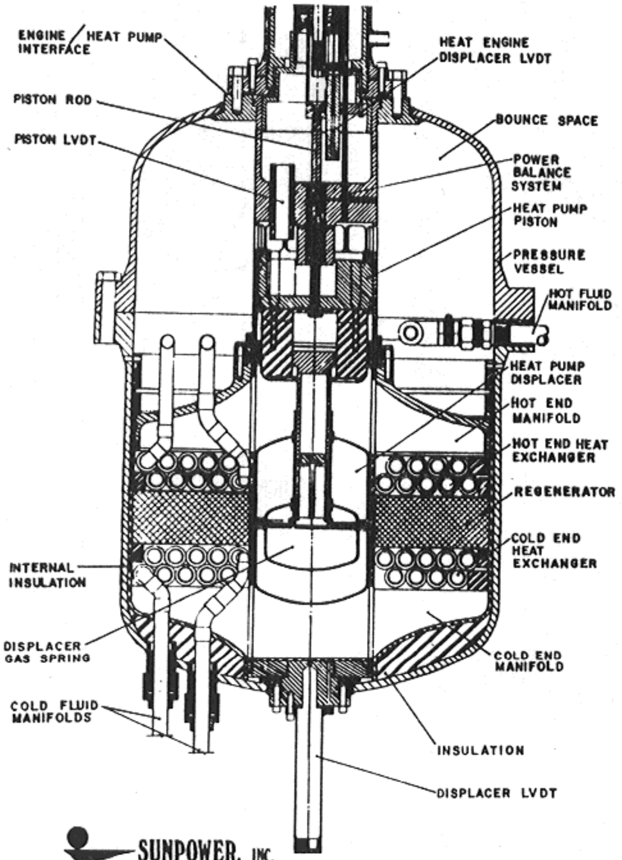


Figure 4

The engine finished fabrication as planned prior to the heat pump and was mounted on a simulated heat pump load so that the engine could be characterized over the range of operating conditions expected when attached to the actual heat pump. These tests confirmed the basic engine design parameters but also uncovered a number of problem areas which required time and attention to detail to eliminate.

The fully assembled and pressure-checked heat pump subassembly was driven through a mechanical linkage with an electric motor
These tests confirmed that the full scale heat pump performed as well or better than the results predicted from the subscale test rig. Final test results indicated that a figure of merit (defined as heat rejected by the heat pump working fluid divided by PV power input to the heat pump) of 3 could be obtained with an external fluid temperature difference of 50C (-3C to 47C). This represents approximately 50% of the Carnot performance potential at these operating conditions, confirming the basic viability of the Stirling heat pump concept. Other critical areas confirmed in these tests were displacer centering, displacer phase control, internal heat exchanger operation and regenerator performance. Results of these tests were employed to further refine computer models used in the design procedure.

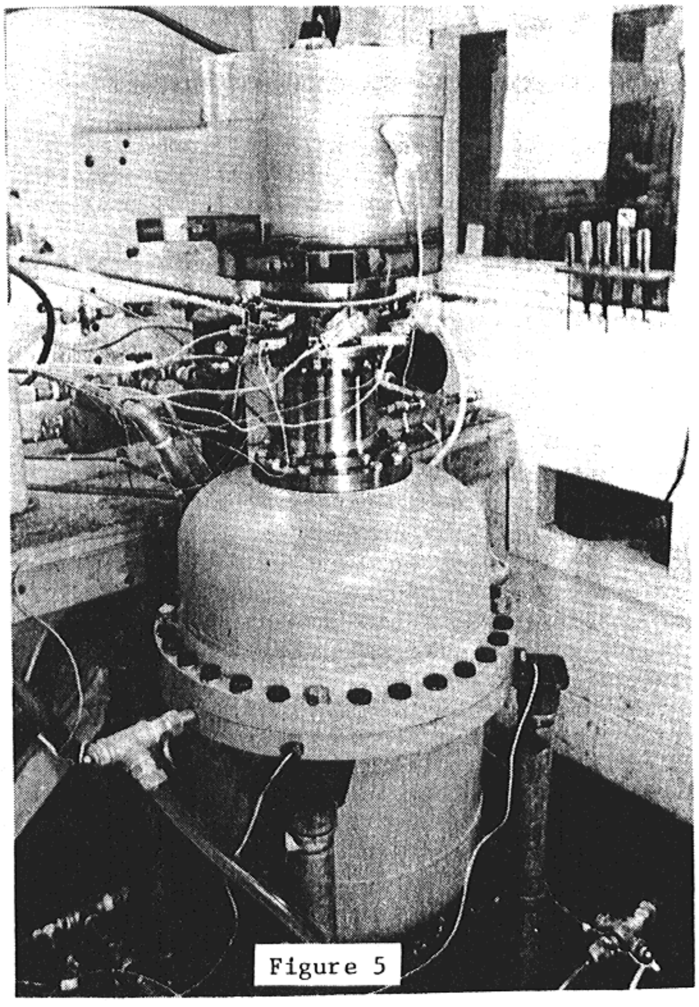


Figure 5

After a number of program changes the sponsor requested a demonstration of the full duplex system (Figure) operating at steady state conditions for reasonable time periods. Performance per se was not as critical as a clear demonstration of stable system operation. This test series was completed with approximately 30 hours of steady state operation attained (the longest individual run being of 4 hours duration). The ability of the heat pump displacer control system to maintain proper displacer operating conditions played a major role in this portion of the test program.

Conclusion

The performance potential of the duplex Stirling heat pump was a matter of much speculation prior to this program primarily due to the considerable unknowns related to the application of the Stirling cycle heat pump portion of the system over the temperature ranges required in a residential application. The findings of this program clearly indicate that this critical component can be successfully designed and operated over the range of required temperatures. When the heat pump is attached to a fully developed Stirling engine, the resulting system COP (heat rejected to load divided by gas energy to burner) will meet or exceed the design goal of 1.5 at the lower rating point.

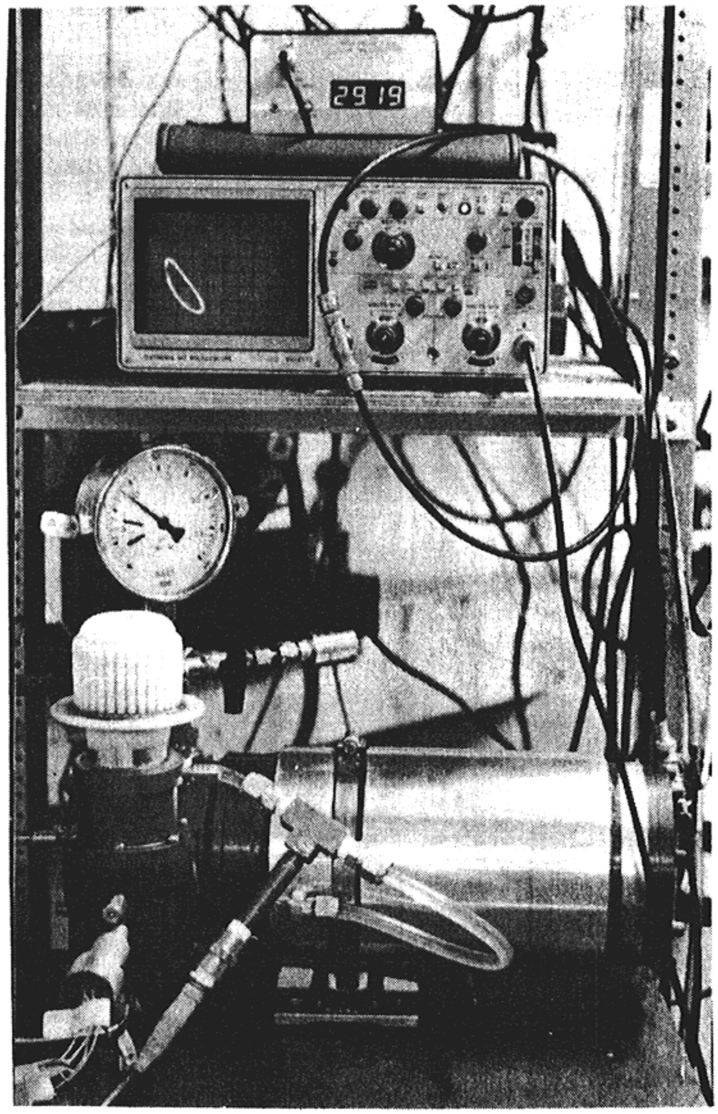
DUPLEX REFRIGERATOR DEMONSTRATOR

This device represents the latest embodiment of the duplex Stirling concept at Sunpower, and is the culmination of a feasibility demonstration study sponsored by the Gas Research Industries (4). The purpose of the program was to fabricate a portable demonstration duplex Stirling refrigerator unit so as to expose this technology to potential appliance manufacturers.

In the design phase of this project an initial thorough investigation of alternative configurations was made. The configuration chosen represents a unique departure from previous devices and allows a maximum flexibility in development. Thus each of the major components (being the piston and two displacer modules) was considered as an independant entity, including its own external heat exchangers and centering control mechanism. This results in a truly modular 'building block' approach allowing a convenience of separate evaluation as well as developmental modifications. Furthermore there are no concentricity problems between the piston and either of the displacer rods, allowing an extremely simple piston configuration. This design approach lead to the concept of a 'Universal Test Rig', by which the system could be separated into its major components and separately tested, evaluated and correlated with the computer predicted performance. This approach proved to be extremely effective, and the system development closely followed the projected work plan.

Normally in the development of a duplex Stirling machine the system must be integrated before its performance can be evaluated. The resulting operation is highly interactive, and it is difficult to isolate or locate component faults or mismatches. The Universal Test Rig enables the individual thermodynamic and dynamic performance evaluation of the components. It consists basically of a variable speed two-piston compressor contained in a helium pressure vessel, and is designed to enable extensive instrumentation which is not accessible in the integrated system. Figure 6 shows the engine displacer module being evaluated on the Rig in the cooling operating mode. With the burner mounted it was possible to evaluate the module performance continuously over the range from -40C to 600C.

Figure 6



APPENDIX -- THE P-P DIAGRAM ANALYSIS

The P-P diagram is a simple laboratory technique for monitoring the performance of a duplex Stirling heat pump. It is obtained by plotting the compression space pressure of the engine vs the compression space pressure of the heat pump. The following analysis shows how this can be used to determine the piston amplitude and mechanical power transferred.

$$\text{Power} = \left(\oint p \cdot dV\right) f \qquad (1)$$

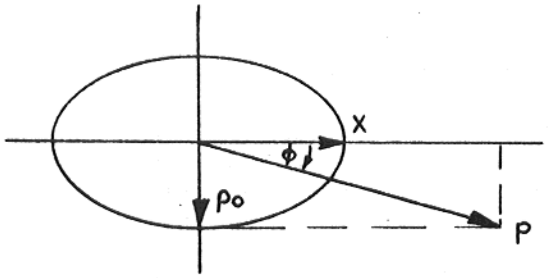
where p is pressure
V is volume
f is frequency

or in terms of piston amplitude variation dX

$$\text{Power} = -\left(\oint p \cdot dX\right) A \cdot f \qquad (2)$$

where A is piston face area.

Real power is produced by the component of the pressure wave which is orthogonal to the piston amplitude, for which assuming sinusoidal pressure and amplitude vectors, the integration path is elliptical, as in the following diagram:



The power out is given by the area of the ellipse, thus:

$$\text{Power} = -\left(p \cdot \sin\phi \cdot A\right) X \cdot \pi \cdot f \qquad (3)$$

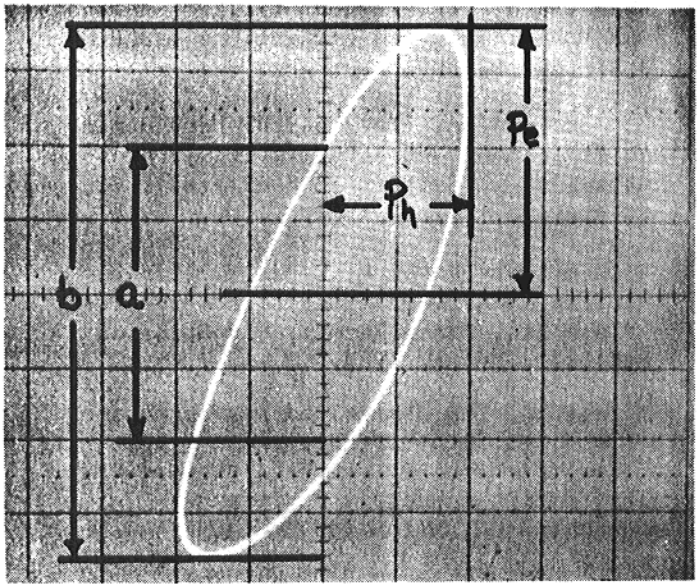


Fig. A.1 The P-P Diagram

In the engine end, the pressure phase lags the amplitude, thus the resulting (developed) power is positive. In the heat pump end the pressure phase leads, resulting in negative (absorbed) power. We assume that all the engine power is used to drive the heat pump using a common piston, thus:

$$\text{Power} = -p_e \cdot \sin\phi_e \cdot A \cdot X \cdot \pi \cdot f$$
$$= p_h \cdot \sin\phi_h \cdot A \cdot X \cdot \pi \cdot f$$

leading to

$$p_e \cdot \sin\phi_e = -p_h \cdot \sin\phi_h \qquad (4)$$

Furthermore the in-line component of pressure determines the piston dynamics, thus:

$$p = p_e \cdot \cos\phi_e + p_h \cdot \cos\phi_h \qquad (5)$$
$$(2\pi f)^2 = \frac{K}{M} = \frac{p \cdot A}{X \cdot M}$$

where K is the effective spring constant
M is the piston mass

leading to

$$X = \frac{(p_e \cdot \cos\phi_e + p_h \cdot \cos\phi_h) A}{(2 \cdot \pi \cdot f)^2 M} \qquad (6)$$

The P-P diagram is typically shown in Figure A.1. Care must be taken to center it on the oscilloscope face, thus the phase difference between the pressure waves are given by:

$$\Delta\Phi = \arcsin\left(\frac{a}{b}\right) \qquad (7)$$

where

$$\Delta\Phi = \phi_h - \phi_e \qquad (8)$$

Substituting equation (8) in equation (4) and simplifying, we gather the pertinent equations in Table A.1.

Given: piston specifications M, A
measured frequency f
pressures p_h, p_e, a, b

$$\Delta\Phi = \arcsin\left(\frac{a}{b}\right)$$

$$\phi_e = \arctan\left[\frac{-p_h \cdot \sin\Delta\Phi}{p_e + p_h \cdot \cos\Delta\Phi}\right]$$

$$\phi_h = \Delta\Phi - \phi_e$$

$$X = \frac{(p_e \cdot \cos\phi_e + p_h \cdot \cos\phi_h) A}{(2\pi f)^2 M}$$

$$\text{Power} = -p_e \cdot \sin\phi_e \cdot A \cdot X \cdot \pi \cdot f$$

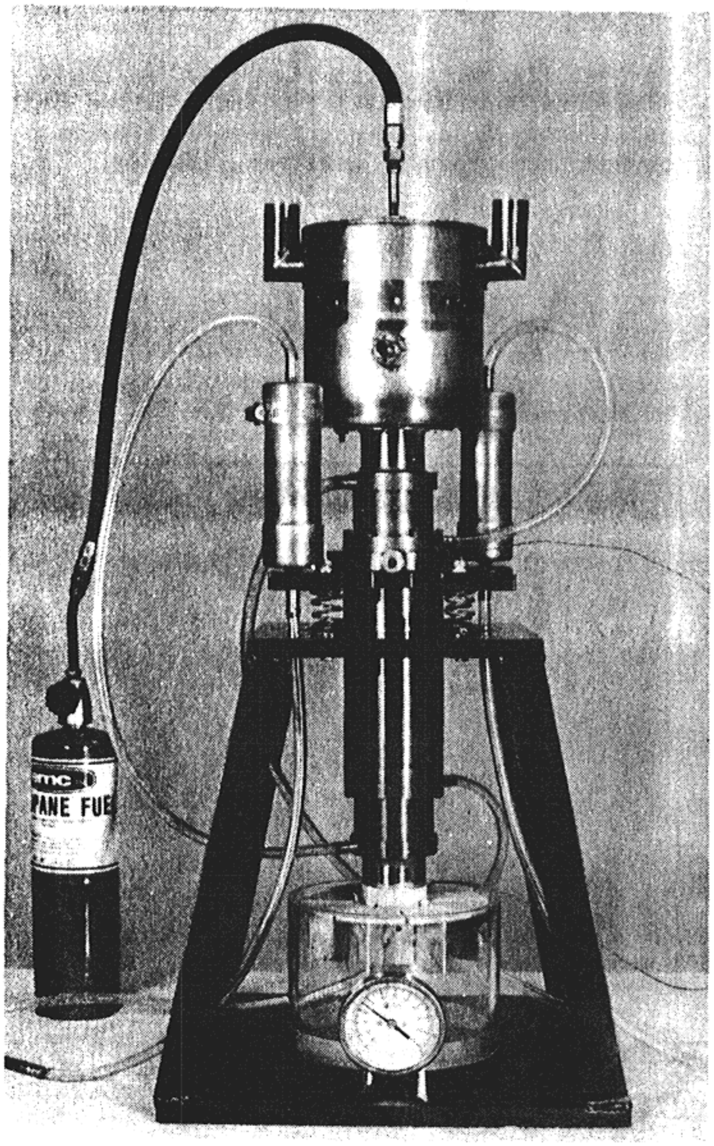
Table A.1 p-p Analysis-Pertinent Equations

On evaluating the system performance it was found that the engine section produces between 30 and 40 Watts of mechanical power, depending on the burner temperature which is typically set at between 500C and 600C. Under these conditions the refrigerator section lifts between 40 and 50 Watts of heat at -20C as measured on the heat exchanger fins. The mean pressure of the working gas (helium) is 10 bar and the operating frequency is about 32 Hertz.

In the duplex device all of the engine power is committed to driving the heat pump. It is extremely difficult to suitably instrument the system to evaluate the engine power output. We developed a unique new technique, by means of which measuring the pressure wave on either side of the piston, both the piston amplitude and engine power output can be monitored (refer Appendix).

Two systems were built, one to be subjected to extensive cumulative testing and evaluation, and the second to be committed to demonstration.

Figure 7



At the time of writing of this paper the system had accumulated more than 1900 hours of operation, showing no significant wear problems.

The completed demonstrator is shown in Figure 7. One of the difficulties of a 'stand alone' demonstrator requirement is the fact that both the engine and refrigerator section are water cooled. The engine rejects a large amount of heat and with a reasonably modest heat exchanger the water heats up to about 45C. This temperature is too high for heat rejection of the refrigerator section since it will not allow the temperature to go below about 0C. The solution was to separate entirely the two heat rejection systems, each with its own self contained engine oscillation activated water pump and 4 liter water container. Within this period a significant frost layer builds up on the refrigeration side of the system. The hot water in the engine water container adequately demonstrates the dual use capability of the system (being refrigeration and water heating).

Conclusion

On successful completion of the project we conclude that the duplex Stirling refrigerator shows great promise as a feasible alternative gas fired system. It is extremely quiet, starts easily, can reach extremely low temperatures if required and has a fast pull-down performance. It runs in a stable manner and is easily controlled. The mechanical simplicity of the free piston device, together with the initial life testing done, indicates that it has the potential of a long life system which can be easily manufactured and maintained.

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