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A STIRLING-RANKINE FUEL-FIRED HEAT PUMP

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ABSTRACT

This paper presents a design for a fuel-fired heat pump. The design combines a free-piston Stirling engine prime mover with a linear compressor Rankine heat pump. This combination is now practical due to recent progress towards commercialization in the major components. Engines of this type are being developed and tested for household sized natural gas-fired cogeneration units. In February 2000, a major manufacturer announced the coming commercialization of linear compressors for refrigeration. In this fuel-fired heat pump design, the engine drives the compressor directly, eliminating the inefficiencies of mechanical to electrical and electrical to mechanical conversions. The combination is hermetically sealed. With no maintenance requirements and the use of non-contact gas bearings, the design promises very long life. Simulated performance data is presented. At 0°C evaporator temperature the system would deliver 3560 Watts at 60°C to the interior of the home while consuming 1852 Watts of natural gas, giving a Primary Energy Ratio (PER) of 1.92. At 40°C delivered temperature, the PER rises to 2.66. In the simplest terms, this design can replace a basement furnace with a quiet, minimum maintenance appliance that uses half the present fuel to generate the heat required.

INTRODUCTION

A heat pump is a device that transfers heat from a cooler to a hotter reservoir, expending mechanical energy to accomplish this work. In an electrically driven household heat pump, electricity is used to generate the required mechanical energy, and the heat is pumped using a Rankine cycle. Where a fuel source such as natural gas is available, a household-sized fuel-fired heat pump offers significant theoretical advantages over an electrically driven heat pump. A fuel-fired heat pump can use the rejected heat of the prime mover to improve the performance in the heating mode and avoid the transmission and distribution energy losses of the electric utility grid. However, in practice, there are limited ways to implement such a heat pump. In all cases a means of generating power from fuel is required.

To generate power from fuel, the choices are reciprocating internal combustion engines, fuel cells, micro-turbines and Stirling engines. The power requirements to drive a household sized heat pump are less than 5 kW, and there are no micro-turbines that can perform with even modest efficiency (>10%) at this power level. Ideally the Rankine heat pump would be driven mechanically, directly from the power generator, avoiding the losses associated with converting the electrical power back into mechanical power. This approach eliminates the fuel cell option. Both internal combustion engines and Stirling machines offer the option of mechanically driving a Rankine compressor directly. However, internal combustion engines are short-lived, high-maintenance machines that require significant noise attenuation. Conventional kinematic (crankshaft output) Stirling engines offer an efficient and quiet option for the power generation but have life limiting bearings and seals.

Two innovative, energy efficient technologies are under development which, when combined, offer an ideal fuel-fired heat pump arrangement. Free-piston Stirling engines are external combustion devices that offer high thermal efficiency (> 30%) at small sizes (< 1 kW). Free-piston Stirling engines with integrated alternating current linear alternators are being developed for small biomass-fueled generators[1] and for domestic cogeneration (combined heat and power) systems fired by natural gas[2]. Free-piston engines eliminate the complexity and life limiting aspects of kinematic machines. The lubricated bearings and seals of the crank mechanism are replaced with non-contact clearance seals and non-contact gas bearings[3], [4]. Such bearing and seals are undergoing life tests in engine applications where over 4,500 full thermal stop/start cycles have been completed[5]. One cooler unit at Sunpower has run more than 39,000 hours in nearly continuous operation, at design specifications, since mid-1995.

Using similar free-piston technology, linear compressors are being developed as replacements for conventional kinematic compressors driven by rotary motors[6]. These linear compressors can be modulated over a wide range of output, do not require oil, and have shown efficiencies up to 30% greater than conventional compressors of the same capacity. Commercialization of such compressors was announced by a major manufacturer in February 2000[7]. Features are described elsewhere[8].

A fuel-fired heat pump could be designed using a free-piston Stirling engine with linear alternator to produce AC power that is then used to drive a linear compressor with electric motor. However, greater efficiency can be achieved by driving the compressor directly with the mechanical motion produced by the engine. Here all losses from converting mechanical to electrical power and back again are eliminated, and a single tightly coupled unit is created. This paper describes a design for such a combination and projects its performance. The heat pump is sized to produce 3.5 kW of heat to a hot water heating system such as those typically found in northern European homes. This unit is not expected to run in the cooling mode and is designed accordingly.

Such a machine should mimic the reliability of its component parts, and the low noise and low vibration characteristic of paired free-piston machines in a combined configuration[9]. Rather than converting fuel into heat at around 85% to 95% efficiency as in a furnace, the heat output of a Stirling – Rankine fuel-fired heat pump is projected at 190% or more of the heat value of the fuel.

SYSTEM DESCRIPTION

Figure 1 shows a schematic layout of the free-piston Stirling engine and linear inertia compressor

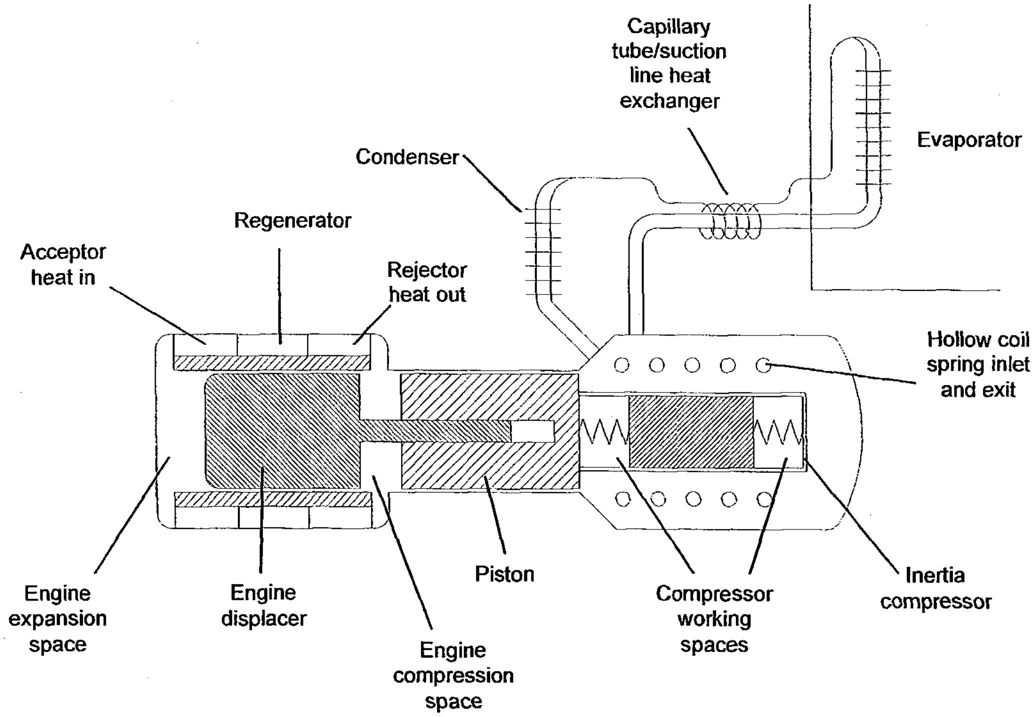

Figure 1: Heat pump schematic

The piston of the Stirling engine moves the housing of the inertia compressor directly. Figure 2 is an artist's rendition of the detailed design; this unit is 480 mm long and 130 mm in diameter.

The Stirling engine has two sinusoidally varying working volumes, termed the expansion space and the compression space. The variation in the expansion space volume leads that of the compression space. In practice, the actual processes of compression or expansion occur continuously and almost simultaneously throughout the entire machine. Two moving elements, a displacer and a piston, produce these volume variations. The heat exchanger comprises three parts, an acceptor, a regenerator, and a rejector. These connect the two working spaces, as shown in Figure 1. Heat is taken into the machine at the acceptor and rejected at the rejector. If the acceptor is at a higher temperature than the rejector, the pressure acting on the piston will lag the piston motion and positive work is produced; the machine operates as an engine. The working fluid in this engine is helium.

The detailed engine design is based upon an existing 1 kW engine. However, here the engine is designed to produce 500 watts of mechanical power. A deep drawn stainless steel can is used for the heater head. Both the internal acceptor and rejecter use folded copper fins brazed to the inside of the head. The regenerator is made of dimpled stainless steel wrapped foil. The external heat transfer surfaces of the acceptor and rejecter are brazed to the outside of the head.

Gas bearings are used on the running surfaces of the piston and the displacer. These bearings are fed from an internal cavity of the piston. This cavity is charged from the working cycle gas by using a small check valve in the face of the piston. This gas bearing system is well proven in existing designs[10].

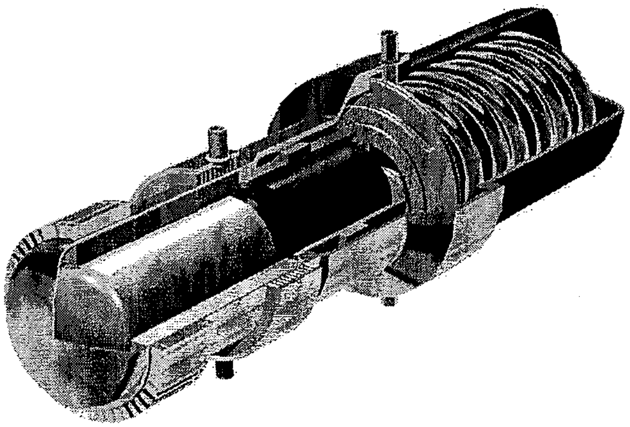

Figure 2: Rendition of the detailed design

The displacer of this machine is mechanically resonated by planar springs. To reduce side loads on the displacer, use is made of a compliant connection system (see ref. 4). The displacer is connected to the springs by a slender rod, sized to transmit the spring force without buckling, thus minimizing side loads on the displacer.

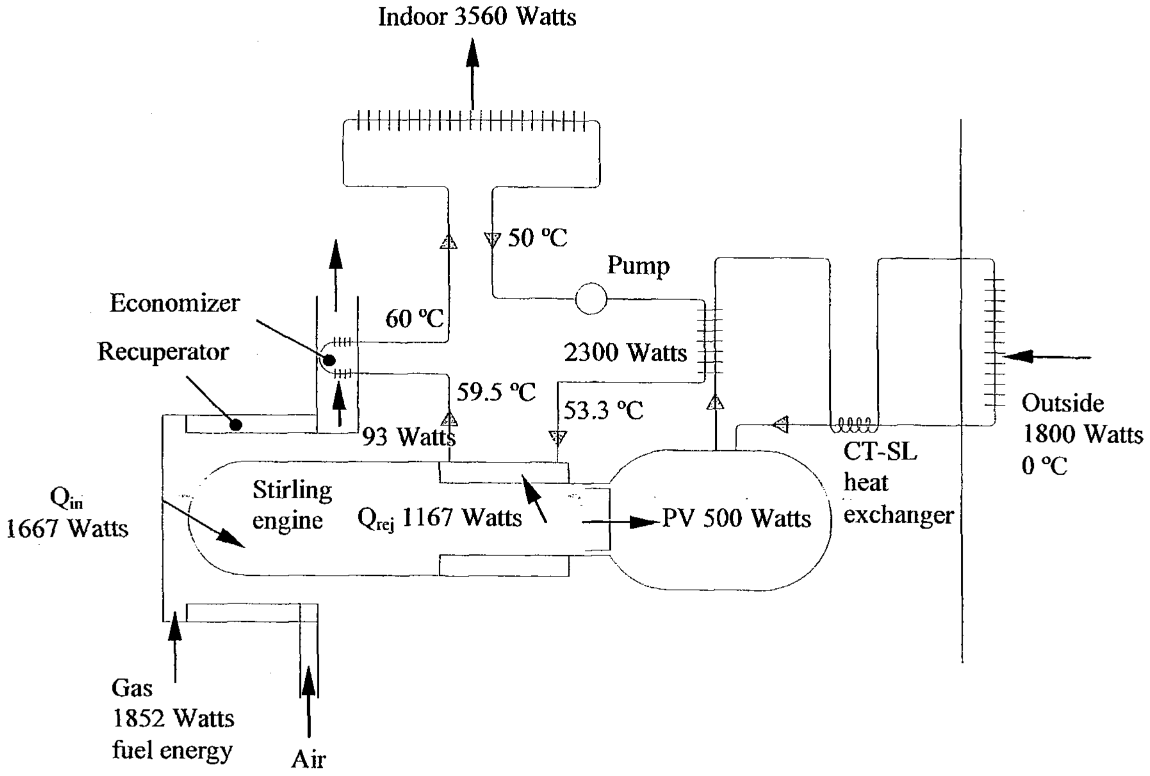

Figure 3: System and design point energy flows

The basic Rankine cycle used here is similar to conventional Rankine systems. In the analysis, R22 is assumed as the working fluid for the Rankine system. Other refrigerants will give essentially the same system performance, though the design pressures across the compressor will be different. The working fluid of the Rankine system, in a gaseous state, is compressed at the compressor. The gas then flows to the condenser where it gives up heat; in doing so the working fluid is condensed to a liquid. Some sub-cooling of the fluid occurs here, to below the condensing temperature at the local pressure. Sub-cooling by 5°C was used in this design.

The next element in the system is a capillary tube-suction line (CT-SL) heat exchanger. The purpose of this heat exchanger is to increase the COP of the system. It would also be possible to increase the COP of the system further here, if some heat were rejected directly to the indoor air by the use of a sub-cooler (in front of, or replacing the CT-SL heat exchanger). However, since the intended application of this design is to deliver heat to a water distribution system, a sub-cooler was not included.

The working fluid, still in the form of a liquid, then proceeds to the evaporator. Here energy is absorbed by the working fluid from the outside air as the working fluid is converted to a gas. It was assumed that the gas is superheated by 10°C. The gas then passes through the CT-SL heat exchanger absorbing more enthalpy before entering the suction side of the compressor.

The only part of the system that differs from a conventional Rankine system is the type of compressor that is used. Since the working fluids of the engine and the heat pump are different, and each must to be sealed, use is made of a double-acting inertia compressor. The compressor housing is made to reciprocate by attaching it directly to the engine piston. The inertia compressor contains an internal free piston supported on gas bearings that is designed to reciprocate out of phase with the housing, thus allowing for compression to occur internally. Sealing and separation of the two fluids while allowing for the movement of the compressor housing is accomplished by using two (nested) coil springs formed from hollow tubing. The Rankine cycle working fluid passes into and out of the compressor by flowing through these hollow-tube coil springs.

PERFORMANCE

Figure 3 shows the heat pump and other elements of the entire system, together with the design point energy flows. The system includes a natural gas burner with recuperator. An economizer is also included in the exhaust stream of the burner. The system includes the pumped loop of the refrigerant and a hot water pumped loop. The latter is used to recover the rejected heat of the engine and the energy retained by the economizer. The system delivers 3560 Watts to the interior of the home while consuming 1852 Watts of natural gas. Therefore the Primary Energy Ratio (PER=heat delivered/energy consumed) of the system at this design point is 1.92. This system was also simulated for other inlet and exit water temperatures; results are summarized in Table 1. Obviously if the unit can deliver lower temperature heat, such as to a forced air system, the PER improves. In fact, the system has a PER of 2.66 when delivering heat at 40°C. The higher PER of the lower delivered temperature systems also has the benefit of requiring a smaller engine and compressor for the same amount of delivered heat

Delivered water temperature (°C)	Return water temperature (°C)	Heat pump outlet/engine inlet water temperature (°C)	Rankine heat pump COP	Engine Power (watts)	Heat Delivered (watts)	System PER
80	70	77	3.35	500	2934	1.58
60	50	57	4.60	500	3559	1.92
50	40	47	5.60	500	4060	2.25
40	30	37	7.35	350	3454	2.66

Table 1: Fuel-fired Stirling – Rankine heat pump: Simulated system performance (0°C evaporator temperature)

An indication of achievable COP/PERs for different heat pump types is given in Table 2, provided by the IEA Heat Pump Center (see ref. 11). For electrically driven heat pumps, a PER can also be defined, by multiplying the COP with the electric power generation efficiency. Existing power generation infrastructure efficiencies are typically at best around 33%, giving the electrically driven heat pumps a PER of 0.83 to 1.65.

Heat pump type	COP	PER
Electric (compression)	2.5 - 5.0	
Engine (compression)		0.8 - 2.0
Thermal (absorption)		1.0 - 1.8

Table 2: Achievable COP/PERs for different heat pump types at evaporation temperature 0 °C and condensing temperature 50 °C (data from IEA Heat Pump Center)[11]. As described in the text, calculated PER for an electrically driven heat pump ranges from 0.825 to 1.65. A fuel-fired Stirling heat pump is projected to have a PER of 2.25 under similar conditions (Table 1, line 3).

The proposed Stirling/Rankine inertia compressor has a higher PER (Table 1) and therefore uses less energy than any existing alternative (Table 2). It should also be noted that the highest PER values of the Engine type in Table 2 relate to large industrial systems. Much lower PER would be expected for residential sized units.

CONCLUSIONS

Where a source of fuel such as natural gas is available, a fuel-fired heat pump offers the potential for substantial energy consumption benefits over an electrically driven heat pump. A free-piston Stirling engine directly driving an inertia linear compressor offers an ideal way to implement such a fuel-fired heat pump. Both free-piston Stirling engines for cogeneration applications and linear compressors for Rankine refrigeration applications are currently being commercially developed. The engine and inertia compressor use a combination of non-contact gas bearings and seals; this complete elimination of wearing contact allows the heat pump the potential to deliver a life of over 100,000 hours. The unit is hermetically sealed; there are no user serviceable parts inside and noise should be less than or equal to current electrically driven devices.

A system including this heat pump will have a PER of 1.92, using 0°C evaporator temperature and delivering hot water at 60°C. At lower delivered temperatures, say 40°C, the PER will be 2.66. No existing electrical or fuel-fired heat pump is as efficient in its use of energy as this proposed combination. Additionally the Stirling-Rankine system maintains a high PER in smaller sizes such as required by the residential heating market. Overall, the fuel-fired Stirling Rankine heat pump will be an alternative to conventional furnaces, and will approximately double the heat generated from fuel, reducing fuel needed by 50%.

Finally, the Stirling engine is an external combustion device and therefore makes minimal demands upon its fuel characteristics. With an appropriately designed burner, this heat pump could use other fossil fuels, either liquid or gaseous. Even renewable biomass could be used as fuel, making a CO_2 neutral heat pump-based heating system. Another result of using biomass fuels would be to essentially double the heat produced from available biomass resources in areas such as Sweden, where renewable biomass is used for heating. No other potential fuel-fired heat pump has this feature.

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