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Marine applications of Stirling engines

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SYNOPSIS

A Stirling engine is a heat engine operating on a closed thermodynamic cycle with compression and expansion of the working fluid at different temperature levels. It may be used as a power system converting heat to work, as a refrigerator or as a heat pump. The only well established present application for Stirling engines is cryogenic refrigeration. Future marine applications for Stirling engines are foreseen as (i) coal-fired main engines in the power range 0.5–5 MW, (ii) silent, low-infra-red-emission power generators and propulsion motors for various naval purposes and for yachts and recreational vehicles, (iii) underwater power systems, and (iv) 'bottoming cycle' waste-heat-recovery units for power generation, pumping and air conditioning.

INTRODUCTION

A Stirling engine is a heat engine which operates on a closed regenerative thermodynamic cycle with compression and expansion of the working fluid at different temperature levels. A comprehensive summary of the technology of Stirling engines was produced by Walker in 1980[1].

Fig. 1 shows one embodiment of a Stirling engine consisting of a piston cyclically reciprocating in a cylinder closed at the upper end. The working space above the piston is divided by another reciprocating element, called the displacer, into the expansion space (above the displacer) and the compression space (between the piston and the displacer). These two spaces are interconnected through ports and three heat exchangers – the heater, the regenerator and the cooler. There are no valves so the pressure in the two spaces is the same apart from minor flow losses.

The regenerator acts as a thermodynamic sponge recycling thermal energy so the regenerative matrix alternately accepts heat from or releases heat to the working fluid. Use of the regenerator is the reason Stirling engines have a high thermodynamic efficiency between given temperature limits.

The heater transfers heat at high temperature from some external source to the working fluid. The cooler transfers heat from the working fluid to the coolant at low temperature.

Some of the heat supplied is converted to external work, available at the engine crankshaft coupled to the piston. The pressure above and below the displacer is virtually the same so that little work is required to shuttle the displacer back and forth causing gas to flow from the hot expansion space to the cold compression space and *vice versa.*

The displacer is driven about 90° of crank rotation ahead of the piston and causes (a) compression (piston ascending) to occur with most of the working fluid in the cold compression space and (b) expansion (piston descending) to occur with most of the working fluid in the hot expansion space. The result is that the pressure varies cyclically in near sinusoidal form resulting in a kidney-shaped P against V positive work diagram and the production of useful work output at the shaft.

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SEALS

Increase in the pressure level of the working fluid increases the energy flow and amount of work produced but increases the duty of the fluid seals, shown in Fig. 1, on the piston and the displacer rod. The minor seal on the displacer body serves simply to cause the working fluid to pass through the heat exchangers rather than the displacer/cylinder annulus.

The piston and displacer rod seals prevent the leakage of working fluid from the working space and serve also to prevent the ingress of lubricant. Lubricant leaking into the working space accumulates in the fine interstices of the regenerator matrix impeding the flow and, with air as the working fluid, may form an explosive mixture in the hot areas of the engine.

Long-lived seals with low power consumption and requiring little maintenance have proved to be the Achilles heel of compact high-performance Stirling engines using low-molecular-weight gases (helium and hydrogen) to permit high speeds of operation. The use of air as the working fluid relieves the seal problem as air is easier to contain than hydrogen or helium. Moreover, it is available everywhere at no cost and so can readily be replenished by a small compressor. Engines with air as the working fluid cannot achieve the same high power density achieved with hydrogen and helium for they must operate at moderate speeds (less than 2000 rev./min).

The use of water as the engine lubricant in conjunction with air as the working fluid eliminates both the matrix contamination and the explosion hazard mentioned above. Of course water is not such a good lubricant as oil but is already widely used in many applications, i.e. oxygen compressors and steel rolling mills. The lubrication requirements in Stirling engines are much less demanding than in diesel engines. There is nothing corresponding to the diesel piston 'top rung' lubrication problem. Furthermore the maximum rates of pressure changes in a Stirling engine are orders of magnitude less than in the diesel combustion process.

STIRLING AND STEAM ENGINES

Like a steam (Rankine cycle) engine a Stirling engine receives heat from an external source (combustion space), converts a fraction of the heat received to useful work and rejects the remainder at low temperature. In both engines the high temperature is restricted to the 'metallurgical limit' of materials used for the hot space. The low temperature for heat rejection depends on the temperature and the availability of the coolant. The greater the difference between the hot and cold temperatures the greater the efficiency and the amount of useful work produced.

Unlike the steam (Rankine cycle) engine there is in the Stirling engine no phase change (boiling and condensing) of the working fluid as it remains gaseous throughout. For this reason the pressure and temperature levels in a Stirling engine

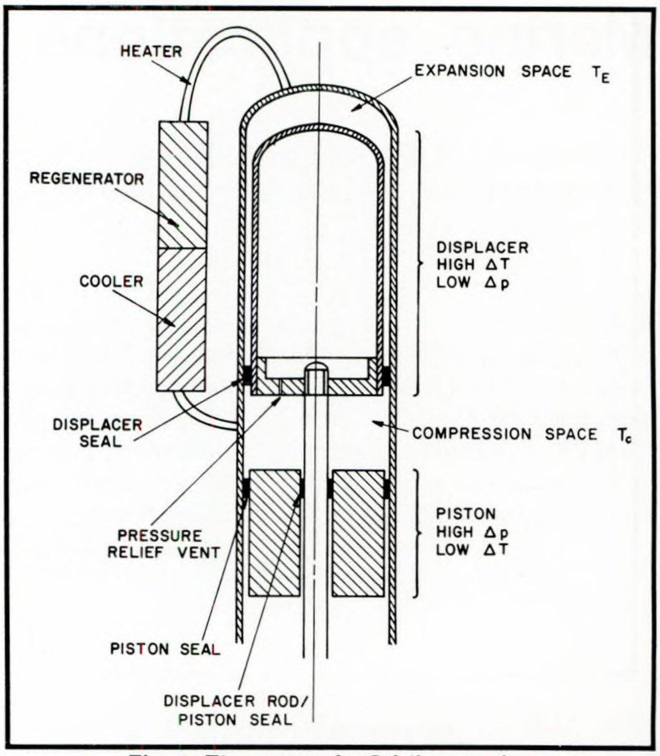

Fig. 1. Elements of a Stirling engine

Fig. 2. Yangtse River passenger ferry

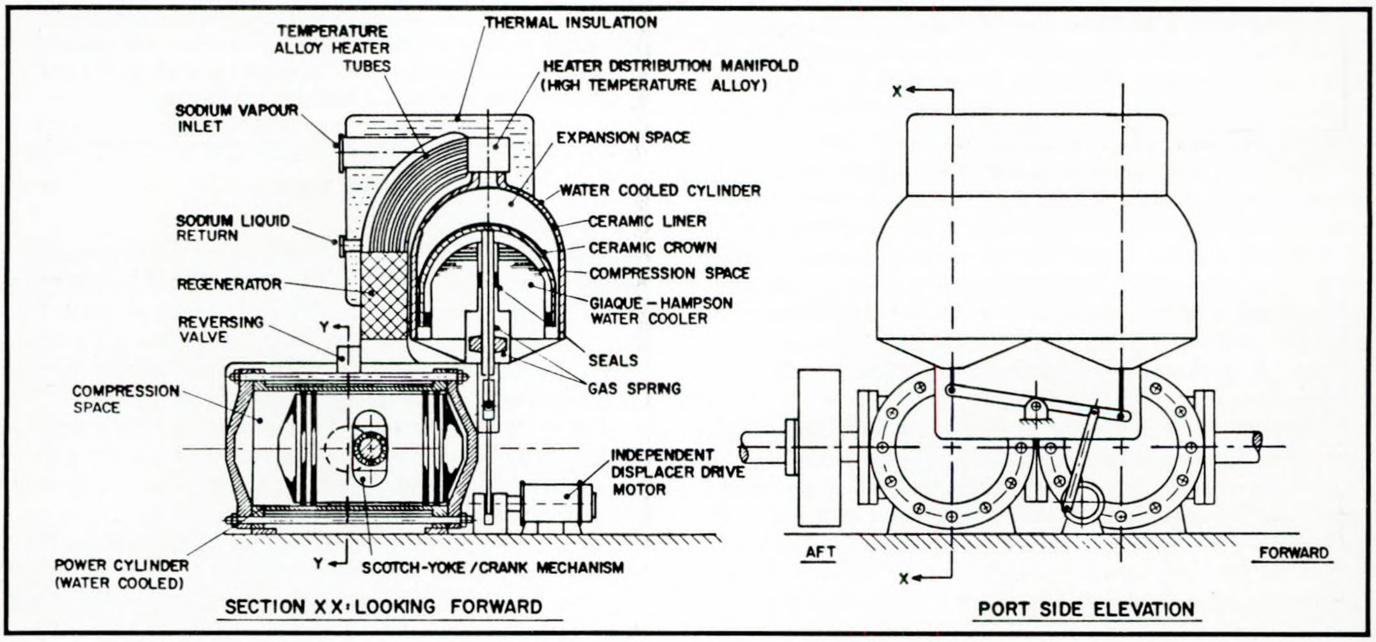

Fig. 3. Concept for Bingham–Stirling marine engine

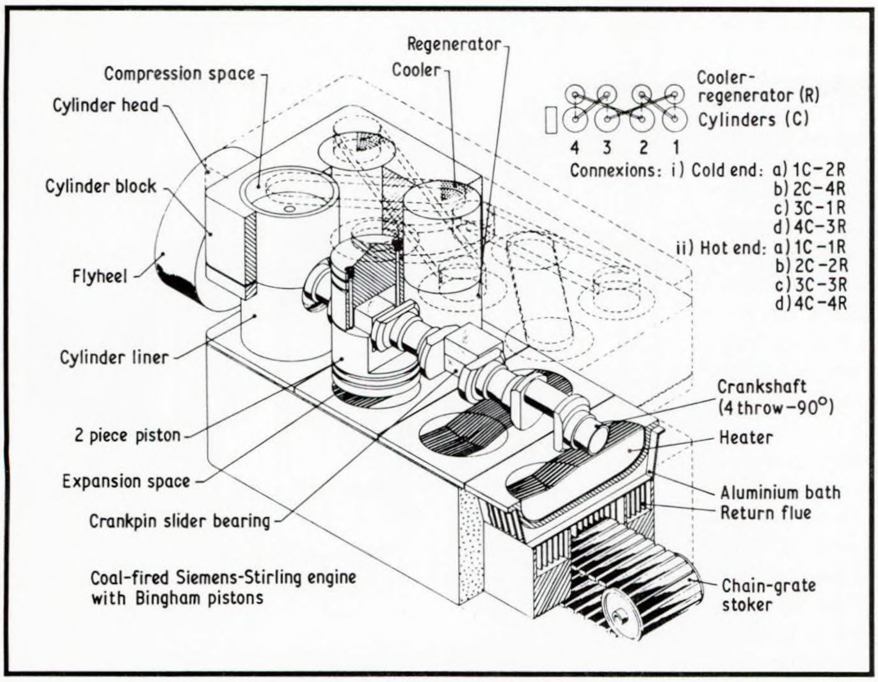

Fig. 4. Concept for Siemens–Stirling marine engine

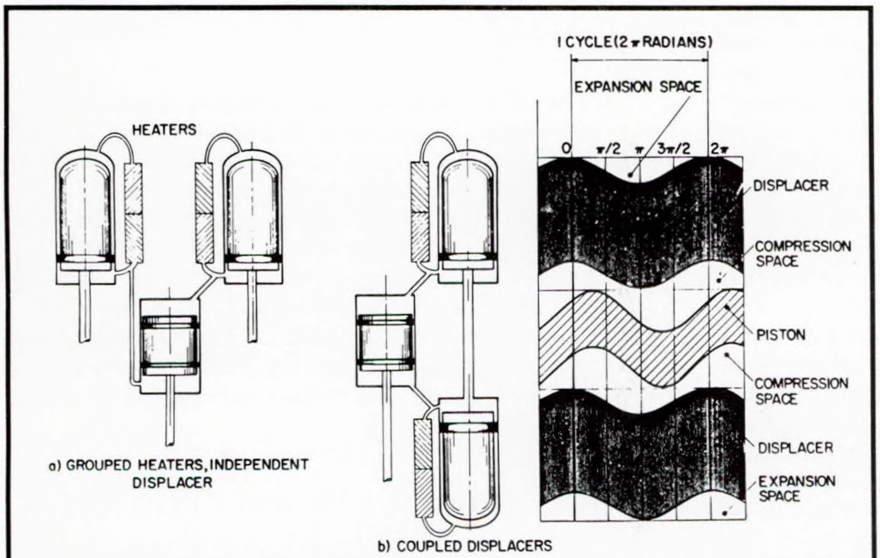

Fig. 5. Diagrammatic representation of a Stirling engine with double-acting piston and separate displacers in individual cylinders

may be chosen independently. At the low cycle temperature the pressure (and hence density) of the working fluid in a Stirling engine may be appreciably higher (several orders of magnitude) than that of condensing steam. As a consequence the size of the Stirling cooler is much less than the equivalent steam condenser.

Incorporation of a regenerative heat exchanger in the Stirling system largely offsets the thermodynamic advantage inherent in the use of constant-temperature heat addition and rejection (boiling and condensing) of the Rankine system. The consequence is that large Stirling engines could perhaps be (a) more efficient than lower-power steam turbines and non-condensing reciprocating steam engines and (b) more compact and as efficient as condensing reciprocating steam engines.

COAL-FIRED MAIN PROPULSION ENGINES

Although any source of heat may be used to energize Stirling and Rankine engines, their future use for main propulsion engines is likely to be limited to vessels where coal is specified as the fuel. The abundance of coal in widely dispersed, politically stable areas and the existing substantial price differential between coal and oil compel serious consideration of its use for main propulsion engines in civil marine use. Valiant efforts to teach diesel engines to use coal have so far proved unavailing. Furthermore, the production of synthetic oil from the hydrogenation of coal is grossly uneconomic.

At power levels greater than 10 MW it is likely that steam turbine Rankine systems will remain as the system of choice with coal firing. The proper niche for coal-fired Stirling engines may then be in the power range 0.5–5 MW. The low power limit will be determined as the level where savings resulting from the lower cost of coal are sufficient to offset the inconvenience of coal usage and the anticipated higher capital costs of the coal-fired system. Small fishing boats are thought to be good candidates for 500 h.p. coal-fired Stirling engines.

YANGTSE RIVER PASSENGER FERRIES

A potential application currently receiving attention for coal-fired Stirling engines are the Yangtse River Passenger Ferries, illustrated in Fig. 2. Some 40 of these vessels ply the Yangtse River from Shanghai to Wuhan, with the majority using twin-screw diesel engines of 2250 h.p. at 285 rev./min. A few of the older vessels are coal-fired with twin triple-expansion steam engines. Both engines and hull are constructed at the Shanghai Shipyard.

Preliminary design studies for the conversion of existing diesel engines to operate as Stirling engines were briefly described by Walker *et al.*[2]. However, the compromises necessary to effect such conversion were so great that, with reluctance, the principle of converting diesel engines to Stirling engines was abandoned in favour of designing the Stirling system from scratch.

Two designs for large coal-fired marine Stirling engines which may prove suitable for the passenger ferry application are shown in Figs. 3 and 4.

The engine shown in Fig. 3 is similar to that illustrated diagrammatically in Fig. 5. A double-acting piston in a cylinder is integrated with twin displacers operating in their individual cylinders to form two separate Stirling systems. The displacers are driven independently (to facilitate engine starting, reversing and speed control). The engine crankshaft passes through the two opposed double-acting pistons and is coupled to the pistons by a Scotch yoke mechanism. This arrangement is said to have Bingham pistons after E. R. Bingham, who first proposed the arrangement in the late 1970s.

The engine shown in Fig. 4 follows the arrangement shown diagrammatically in Fig. 6, where four cylinders, each containing a single reciprocating element, are interconnected so the hot space (above the piston) of one cylinder is coupled through a heater, regenerator and cooler to the cold space (below the piston) of the adjoining cylinder. This double-acting arrangement, conceived by Sir William Siemens in the 1860s, has the advantage that only one reciprocating element is required per Stirling system instead of the two required in single-acting Stirling systems. Configurations of three, four, five and six cylinders may be devised.

A particular advantage of the Siemens–Stirling arrangement is the ease of reversal. In the forward direction the hot space of one cylinder is coupled to the cold space of the succeeding cylinder. To cause the engine to reverse it is necessary only to couple the hot space to the cold space of the preceding cylinder. A relatively simple valve in the ambient temperature region may be used to effect this flow switching and so cause engine reversal. The same switch valve may also be used to interconnect simultaneously all the spaces thereby 'spoiling' the pressure characteristic and putting the engine in a zero power condition.

Fig. 3 shows an engine heated by condensing sodium vapour, itself vaporized in an adjacent fluidized bed coal combustor. Fluidized bed combustors allow the use of high-sulphur, dirty coal requiring minimal preparation or processing with low environmental impact. Use of a sodium heat pipe allows great flexibility when locating the engine and coal combustor as well as permitting very much better operation of the heater. However, large sodium heat pipes and large fluidized bed combustors are both at the development stage and involve special materials and unconventional engineering procedures.

Fig. 4 shows an engine with conventional chain grate stoker combustion and combined radiant/convection heating of an intermediate molten aluminium bath permitting the same 'thermal flux transformer' effect (low input flux on a large area with high output flux on a small area) gained with a sodium heat pipe. The chain grate stoker system requires less advanced technology than the fluidized bed with a sodium heat pipe but reduces the flexibility of the engine configuration and arrangement.

STIRLING AND DIESEL ENGINES

Stirling engines are often regarded, mistakenly, as competitors of diesel engines. Stirling engines can of course use diesel oil as a fuel and can achieve the same brake thermal efficiency as diesel engines. Furthermore, they have the same flat part-load characteristic that makes the diesel engine so attractive.

However, the initial cost of a Stirling engine is, perhaps inevitably, at least 2- to 3-times the cost of diesel engines of the same power. Stirling engines need stainless steel, refractory metals or ceramic components for the hot parts. Furthermore, there are several heat exchangers – the heater, regenerator and an exhaust gas/inlet-air preheater, as well as the cooler found on diesel engines. Inclusion of the exhaust gas/inlet-air preheater is vital if efficiency is an important consideration, for any heat escaping to exhaust from a Stirling has simply not passed into and through the engine. Thus a preheater is required to reduce the exhaust stack loss to approx. 5% of the inlet heat.

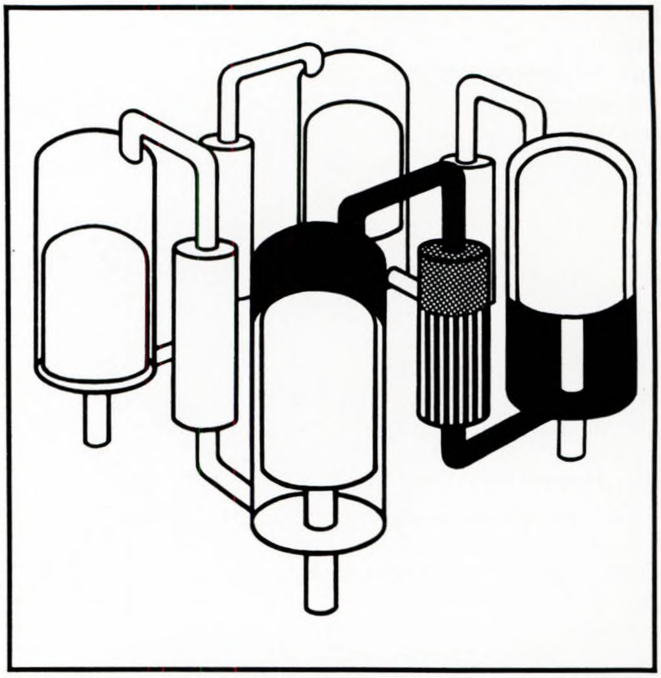

Fig. 6. Square-four Siemens–Stirling arrangement

In a diesel engine the energy distribution is approximately one-third to work, one-third to the cooling system and one-third to exhaust. In a Stirling engine the exhaust loss must be reduced to a low value so the balance must be rejected by the cooling system. Thus, for engines of the same power output and efficiency the cooling system of the Stirling engine must handle about twice the energy flow of diesel engines. This is an important constraint in mobile equipment, locomotives or heavy off-highway vehicles used for mining, construction, forestry and agriculture. It is less important in marine systems where the vessel floats on a virtually infinite sink of cooling medium.

SILENT STIRLING ENGINES FOR NAVAL AND MILITARY USE

For the reasons given above (i.e. cost), there are few civil applications where a Stirling engine operating on diesel oil, gasoline or propane would be used in preference to an internal combustion engine.

However, Stirling engines do have two significant advantages over diesel and gasoline engines. First they run without noise, virtually as silent as sewing machines, and secondly they have a low-temperature exhaust. The lack of noise arises because there are no valves or periodic explosions of the fuel + air mixture in the cylinders. The low-temperature exhaust arises naturally as a consequence of the exhaust gas/inlet-air preheater required for reasonable efficiency. In addition, since combustion occurs continuously and at atmospheric pressure in a chamber with hot walls the combustion products are very clean with virtually no unburned hydrocarbons. Recirculation of a significant percentage (25%) of the products of combustion reduces the formation of NOx (oxides of nitrogen) to an insignificant level.

The civil applications, where the advantage of a liquid fuel and a quiet engine having a low-temperature and non-polluting exhaust justify a premium of 3-times the capital cost of a diesel engine, include sailing boats (yachts) and recreational vehicles (in themselves an uneconomic extravagance). There are other possibilities for underground mining equipment on the grounds of health and safety. In the main, however, the principle applications for silent, low-temperature exhaust Stirling engines operating on diesel oil, kerosene and gasoline are naval and military.

There is, for example, a naval requirement for a 50 kW power generator onboard submarine chasers to maintain a weapons and communications capability while in a search and surveillance mode of operation. Other naval applications are foreseen for nocturnal surveillance craft, rubber assault boats and similar applications where stealth is important. An engine with a low-temperature exhaust is attractive because it foils detection by infra-red-sensing scanners and does not attract missiles with heat-seeking infra-red guidance systems.

The advantages of quiet operation and low infra-red emission are equally important for battlefield applications. Use of existing fuels is imperative to reduce logistical problems and the Stirling engine has the further advantage of wide ranging multi-fuel capability. It can operate happily on any liquid or gaseous fuel with minor adjustments to the fuel system.

UNDERWATER POWER SYSTEMS

Another use for which the Stirling engine is well suited is underwater power systems. It can use any combustible fuels as the energy source, thus diesel fuel/cryogenic oxygen have been used as well as metal combustion with an 'oxidant', i.e. lithium metal and freon. This latter generates products of combustion which condense at a relatively high temperature permitting onboard storage of the products. This is a particular advantage for deep submergence torpedoes.

Another possibility is a thermal storage 'battery' at relatively high temperatures (800 °C). A lithium hydride thermal battery used in conjunction with a Stirling engine results in a power system half the size and weight of the corresponding electric motor and battery combination. Walker[1] has reviewed the underwater power systems application and more recently Carlqvist *et al.*[3] have given details of the current French Comex project for a small submarine propulsion system.

STIRLING ENGINES IN BOTTOMING CYCLE OR EXHAUST HEAT RECOVERY SYSTEMS

Applications may exist for Stirling engines utilizing the waste heat of exhaust streams of diesel and gas-turbine main engines. Stirling engines can be used whenever a temperature difference exists. Recently Kolin[4] and Senft[5] have demonstrated Stirling engines operating well on the temperature difference of hot and cold water (i.e. less than 100 °C). Similarly in Japan the generation of power is proposed using Stirling engines 'heated' by sea water at ambient temperature (300 K) and cooled by liquid natural gas (100 K). The objective, of course, is to vaporize the liquid natural gas but the production of electric power in the process does recover some of the millions of horsepower invested in the original liquefaction of the gas.

In the so-called 'bottoming cycles', an engine energized by waste heat generates some power that is deployed to supplement the output of the main engine. Unfortunately such systems are rarely worthwhile and an exhaust gas/inlet-air preheater is almost always more effective. However, there are situations where an engine energized by exhaust heat can be profitably incorporated to complement or replace independent auxiliary generators for refrigeration, air conditioning and the other multiple power or pumping requirements on board ship.

STIRLING REFRIGERATORS AND HEAT PUMPS

An unusual but engaging characteristic of Stirling engines is that they can be used as refrigerators and heat pumps as well as power systems. Returning to the configuration of a Stirling engine shown in Fig. 1, it will be seen that this system will operate as a refrigerator if the heat supply to the expansion space is simply terminated while the engine is sustained in operation by feeding work into the system via the piston rather than extracting work from the system as in the power application. Heat continues to flow into the heater and the expansion space during expansion. Since the high-temperature supply has now been discontinued the surrounds of the heater and expansion space become cold and low-temperature refrigeration is produced. This refrigeration capability of Stirling engines is so effective that the cylinder head and heater become cold enough for air to liquefy on the cylinder head (about 80 K). With multiple expansion systems even lower temperatures may be routinely attained: 6–10 K with four stages of expansion and 3.5 K with five stages.

Its use as a cryocooler, a refrigerator operating at cryogenic temperature levels, is the principle present application of Stirling engines[6]. Miniature machines are in volume production for military applications in night vision infra-red equipment and missile guidance systems. There is a rapidly increasing usage for diverse civil, medical and scientific applications involving low-temperature superconducting electronic systems.

Stirling heat pumps work in precisely the same way as Stirling refrigerators. The difference is simply in the relative levels of temperature. A heat pump absorbs heat at ambient temperatures and rejects heat at super-ambient temperatures. The rejected heat is used primarily for space heating. A refrigerator absorbs heat (the refrigeration process) at sub-ambient temperatures and rejects heat at ambient temperatures.

Both refrigerators and heat pumps require an input of work to effect their operation and this can be provided by another Stirling engine acting as a power system, accepting a high-temperature heat input (perhaps the exhaust gas stream of a diesel or gas-turbine engine). This arrangement is often referred to as the duplex-Stirling or Stirling–Stirling system.

Any temperature difference can be utilized to drive a Stirling engine to generate a power output. In the same way any energy stream at some temperature level can be 'pumped' to a higher temperature level using a Stirling engine with a suitable power input. For those with an inclination to thermodynamic analysis approximate calculations may be made assuming that power systems will achieve 50% of the Carnot value and that refrigerators and heat pumps will achieve 40% of the Carnot value.

CONCLUSIONS

Stirling engines are not widely used at present except as cryogenic refrigerators. It is possible their future use in marine propulsion applications may include coal-fired main engines in the power range 0.5–5 MW, and as quiet engines having clean, low-temperature exhaust in special naval applications and for yacht power systems. Other possibilities exist for their use as underwater power systems and for bottomiing cycle, waste-heat recovery, power generation, pumping and air-conditioning systems.

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