STIRLING ENGINE MICRO CHP

INTRODUCTION

Combined Heat and Power (CHP) has significant potential for the more efficient use of fossil fuels and the reduction of CO_2 and other polluting emissions. It also offers the possibility of reduced infrastructure requirements, (and consequent environmental impact) both in terms of large scale generators and the associated transmission and distribution facilities, by the nature of "embedded" generation. Indeed, the evolution from central generating plant to distributed generation is seen by many as a natural response to environmental demands and to the commercial pressures imposed by an increasingly competitive market.

In the UK, economic considerations limit existing CHP technologies to the size range of 30kWe and above, although tax advantages make 15kWe (and even smaller) viable in some countries. This is primarily due to the high unit maintenance and capital costs of equipment. The internal combustion engines generally applied are of limited durability, reliability and efficiency and produce relatively high levels of noise and air pollution.

Stirling Engines offer better energy efficiency and reliability, lower exhaust emissions and noise levels. They also permit a greater flexibility than internal combustion engines in the choice of fossil fuels and alternative renewable energy sources. Stirling engines are potentially prime movers in CHP systems on the micro scale, operating effectively at outputs as low as 800We.

HISTORY

The Stirling engine is an external combustion engine invented in Scotland in 1816 by Robert Stirling. The Stirling engine principle was historically successful in a number of applications such as rotating fans and for pumping.

The modern development of the Stirling engine was started by the Philips company in Holland, and today Philips has a company in the cryogenics field using the results of their development work for the commercial production of very low temperatures.

In Sweden, United Stirling was created, with licence rights from Philips and started extensive development work on the Philips Stirling engine in 1968 for automotive and later, solar and submarine applications.

The vehicle application was developed together with American car manufacturers, but could not dislodge the established diesel and Otto engines. There remained problems of complexity, power density and the high cost of engine regulation. However, the development of a large engine has resulted in commercial success in the submarine propulsion market.

TEM (a technology transfer institution at the University of Lund in Sweden) started research and development work on a small scale Stirling engine in 1986. The basis for the development was the new Stirling engine invention made by one of the leading Stirling scientists in the world, the late Professor Stig Carlqvist. He was the leader of all the Stirling development work in Sweden and started the development work at TEM with a small hermetically sealed Stirling engine together with other leading researchers and designers in the Stirling field. The first goal was to create a battery charger for electric cars. Although the interest for hybrid electric cars has not yet been fully realised, the engine has shown promise as a basic component of a CHP system. That was not obvious in Sweden, due to the very high gas prices and relatively low prices for electricity. (Even that premise has changed recently with the imminent closure of the Barseback nuclear power plant, leading to calls for environmentally sound replacement capacity.) However, there is a large potential for the TEM engine in CHP systems in countries where electricity is significantly more expensive than gas.

The Stirling engine principle

Stirling engines are closed cycle engines characterised by an external heat supply. An external heat supply allows the use of any heat source operating at a sufficient temperature level.

The Stirling engine operates by continuous heating and cooling of a fully enclosed working gas. The alternate compressing and expanding of a fixed amount of high pressure helium gas is transformed into a rotating movement to which the electric generators are connected. The continuous external combustion process of the Stirling engine provides good combustion control and low exhaust emission levels. Within the closed Stirling cycle, pressure variations of the working gas follow an almost sinusoidal curve, which is one of the basic reasons for the low noise and vibration level of a Stirling engine. Another reason for the low noise is that there is no connection between the working gas and the outside atmosphere as opposed to the exhaust pipe of an IC engine.

Compared to internal combustion engines, heat losses in a Stirling engine are more concentrated into the cooling water. This characteristic can be utilised to allow the Stirling engine to provide the necessary heat for hot water requirements in a house.

The TEM engine

The main goal for the TEM development work was to achieve a small, reliable, low priced Stirling engine with good long term running characteristics. The result now is a single cylinder, completely sealed Stirling unit with a high potential for low cost manufacturing, high efficiency, low emissions and long life with low maintenance requirements. The present burner design is based upon natural gas, but there is potential for other liquid or gas fuels to be used.

Any machine such as the Stirling engine which contains a special working medium needs to be hermetically sealed in order to guarantee the containment of the working medium, as for example in a refrigeration compressor. This is also possible with a Stirling engine, due to the Carlqvist innovation.

The Carlqvist innovation is to enclose the working mechanism and generators within a completely sealed pressurised crankcase with permanently lubricated, oil-free, anti-friction bearings. This closed system solves one of the fundamental problems of earlier Stirling engine designs, namely the leakage of Helium and lubricants.

The pressurised crankcase design eliminates the need for a high performance, high loss connecting rod seal between the power piston rod and the displacer piston rod. This contributes to increased mechanical efficiency. As it was then possible to integrate the electric generators within the crankcase, the need for a cross head was then eliminated, contributing to a further decrease of mechanical losses, and to a reduction in crankcase volume.

Experimental Stirling Engine CHP units

A number of experimental engines based upon the Carlqvist innovations have been built and tested in the TEM laboratories in Malmö, Sweden. These engines are dimensioned for an electrical output of 3 kW. The displacement volume is 75 cm^3, the working medium is helium, and the motor has a designed rotational speed of 3,000 rpm.

As has been mentioned earlier, this engine was developed for automotive range extender applications, where weight and specific power are major considerations. However, in stationary applications, issues such as service intervals, reliability, durability and low noise levels are more important. It was therefore decided to modify the design to run at lower speed (1500 rpm). This implies a larger cylinder and consequent increases in weight. However, it also increases service intervals by up to a factor of four and should also help to achieve noise levels of below 35dBA suitable for domestic installations. Other modifications have led to improvements in performance so that from an input of 12.5kW of natural gas (gross calorific value) a total of 9kWt (heat output) and 3kWe (electrical output) is obtained. Although it is misleading to talk of “overall efficiency” as there are both electrical and thermal outputs it may be considered that 96% of the fuel input is converted into useful energy. However, it must always be remembered that the electrical output is the more valuable and efforts should be made to maximise this element. Indeed, although much of the work on the TEM unit has focused on the engine itself, the efficient utilisation of the engine is largely dependent on system integration and it is this feature which forms a major component of the THERMIE project which will be described later.

The CHP application

The TEM Stirling engine can be used as a CHP unit where the proportion of the total energy input that can be recovered in useful form as electricity and hot water is very high. It is possible to reach a very high total efficiency because there are very low transmission and distribution losses in the electricity distribution, and because the cooling water can be used directly for heating purposes in the house. In common with other Stirling engines, heat recovered from the exhaust gases is used to preheat the cold combustion air, improving mechanical efficiency. This has greater value than the conventional CHP practice of heat recovery to the cooling water.

EU THERMIE DEMONSTRATION PROJECT

In 1993, EA Technology produced a design study for a micro CHP unit based on the TEM SCP-75 Stirling Engine. This unit was developed by TEM in Lund, Sweden, as result of their work on hybrid automotive units. In 1996, Sigma Elektroteknisk in Norway acquired the manufacturing rights to the TEM engine and plan to supply the unit which they call the "Personal Combustion Powerplant (PCP)" as a component to system packaging companies.

Amongst the potential applications for the PCP is micro CHP, small enough for the requirements of the European residential and small scale commercial market. EA technology are co-ordinating a project funded under the EU THERMIE programme to evaluate and demonstrate the Sigma/TEM PCP in what promises to be the first full scale application of micro CHP in Europe.

The objective of this programme was to install four completed Stirling engine CHP units in representative European installations. Two of the installations will be in public sector housing in UK and two in Denmark. (An additional system is now planned for trials in Norway, where there is some controversy about the construction of central CCGT generating plant on the West coast.)

It is anticipated that the trials will identify any technical, commercial or legislative issues in a European context and enable the experience to be transferred throughout Europe. In each case the electricity supply companies with responsibility for supply in that area have been selected as project partners, both for administrative convenience and technical expertise.

The UK and Danish systems will be installed in existing homes. These have been selected because:

1) the majority of houses with suitable thermal characteristics are existing family houses
2) new homes may be more effectively served by reducing the energy requirement by design rather than reducing the impact of established energy demands
3) gas boiler replacement is a substantial market and will remain so for the foreseeable future
4) we have available current energy use figures for an extended period for these properties which may be used to validate the projected energy savings

The specific objectives are:

- to demonstrate the technical and commercial viability of the Stirling engine micro CHP system when applied to domestic/small commercial installations

- to determine the matching of electrical and thermal load profiles in these applications
- to evaluate the user reaction to the micro CHP unit and the effect on the building and unit performance
- to evaluate the implications of integrating micro CHP systems with different electricity distribution system (e.g. single phase in UK, three phase in Denmark) particularly with regard to the potential DSM benefits

EA Technology has undertaken extensive market research and business planning in collaboration with manufacturing and marketing organisations with a view to determining the optimum electrical/heating specification for a range of CHP units of which the 3kWe model is the demonstration unit. This has indicated the potential market for the micro CHP unit and it is now proposed to proceed to the demonstration phase of the programme with a view to eventual commercial exploitation. It is believed that a potential market of 35 000 systems per annum exists for the current model (3kWe) and up to 165 000 for a range of units in the UK alone.

It is expected that this demonstration project will result in:

a) demonstration of the technical and economic viability of an SE/CHP unit suitable for use in individual houses and small commercial premises.
b) demonstration of the reliability , availability and low maintenance costs of the SE/CHP system
c) demonstration of the practicality of the system from the householders daily use point of view

STATE OF THE ART

Combined Heat and Power is a well proven concept using a variety of generator types and energy sources. However, the majority are many times too large to be relevant to the small commercial or individual residential properties to which this project is directed.

The smallest units generally available are over 8 kWe (although a 5.5 kWe and even 3kWe are being introduced in Germany) and at this size are of questionable economic benefit. They use spark or compression ignition internal combustion engines adapted from automotive versions in order to minimise initial cost. Consequently they have short service intervals, high maintenance costs and limited life. Due to their combustion characteristics they also produce high levels of CO_2, SO_2, and NOX as well as being relatively noisy and are therefore unsuitable for domestic installations.

Stirling Engines, being external combustion machines, have a number of advantages in terms of reliability and performance and ultimately should have a cost between that of spark and compression ignition automotive units. Service intervals of between 3,500 and 5,000 hours (equivalent to more than one year's economic operation) are expected compared with 750-1000 hours for IC engines. (Claims of longer service intervals are normally based upon oversized components such as large oil reservoirs which cannot be applied in normal domestic systems). Life expectancy should be 50-60,000 hours compared with 10,000 hours for an IC engine and it is these characteristics as well as the reduced emissions which the project aims to demonstrate.

The TEM SCP1 75 unit has demonstrated overall efficiencies in excess of 90% and produces 3kWe together with around 9 kWt, although due to the differing fuel cost conditions pertaining to Sweden, no attempt has so far been made there to apply the concept to CHP. It is anticipated, however, that the technology will be viable in those countries where natural gas is widely available and there is a significant cost difference between electricity and gas.

ECONOMIC, SOCIAL & TECHNICAL BENEFITS

Although the proposed installations are very modest in terms of energy production, savings and capital costs, they are nevertheless significant in that they form the basis for substantial replication in the UK, Denmark and throughout Europe.

CHP at any scale reduces the emission of CO_2 and other pollutants and makes more efficient use of finite energy resources. The useful heat supplied by the TEM unit is virtually the same as for the conventional gas boilers it is expected to replace. As the generation is led by thermal demand, it may be considered that the heat is produced at no additional cost over the current situation, but that the electricity is effectively provided free of charge or environmental impact.

The main economic benefit to the end user will be in the form of reduced energy bills by reducing "bought in" electricity consumption and through the export of surplus generated electricity to the network. This clear economic benefit to the end user enables society to obtain the broader environmental benefits without resorting to legislation or costly artificial incentives.

DSM and other utility issues

The electricity utilities may be able to avoid the cost of constructing additional generating capacity and the associated reinforcement of the distribution infrastructure, which will also be of major environmental benefit.

Distributed generation offers the potential for the most effective use of primary fuel. In conventional, centralised plant, as little as 30-40% of primary fuel is converted into usable energy at the point of use. Even CHP with district heating cannot achieve the conversion rates of 95% and over possible with micro CHP. In addition to the energy losses associated with any centralised system, there are considerations of environmental impact of the generating plant and the distribution system, not to mention the capital and maintenance costs of the infrastructure. This is particularly important in developing countries such as Eastern Europe with poor existing infrastructures.

SCOPE

A report by the Energy Efficiency Office has indicated technical potential for small scale (5-20kWe) engines as 3000MWe on a total of 270 000 sites in the UK.

Initial EA Technology studies indicated a potential for an additional 1000MWe at the micro scale (3kWe) on a total of 200,000 sites. However, as market conditions and technical performance develop and environmental demands increase, it is now believed that a potential of several times this figure exists. Even modest levels of market penetration would, however, yield substantial long term savings in CO_2 emissions and fuel consumption.

The combustion characteristic of Stirling engines also offers a significant reduction in other atmospheric contaminants compared with internal combustion engines including large scale turbine systems. It is a major improvement on existing coal fired generation even where advanced scrubbing techniques are applied. It is assumed below that the displaced generation will be at the margin, i.e. the most inefficient and polluting form of generation which is based on older, pulverised coal fired processes without flue gas desulphurisation.

The annual reduction in emissions achieved by each SCP1-75 Stirling Engine is 8.8 tonnes CO_2, 136 kg SO_2 and 50.4 kg NOX. The eventual market for the units is estimated at 1 GW in the UK and 4.5 GW throughout Europe within 15 years. Thus the potential for reduction in emissions is 2.9 million tonnes CO_2, 45,000 tonnes SO_2 and 17,000 tonnes NOX in the UK and a total of13 million tonnes CO_2, 204,000 tonnes SO_2 and 76,000 tonnes NOX throughout Europe as a whole.

THERMIE project structure and principal tasks

The project has two main groups of tasks:

Design, assembly and testing of modified Stirling Engine micro CHP unit

The SCP 1 75 unit incorporates a DC generator suitable for battery charging in automotive applications. The integration of an induction generator is necessary for efficient CHP generation and integration into the network. This raised a number of development issues, such as isolation and control in the event of mains failure. Consideration is also being given to possibilities for design improvements for economic production.

Prior to installation of the unit in the demonstration sites, detailed laboratory tests and studies are being undertaken to validate the performance of the system in use, including emissions, likely modes of failure and output characteristics.

Design, installation and monitoring of systems incorporating Stirling Engine CHP unit.

The main objective of this stage is to install and monitor the experimental units in buildings typical of the target market. There will be an emphasis on overcoming the practical problems of economically running the unit as part of the building services during a complete annual cycle.

In order to maximise economically viability it is desirable to optimise own-use of electricity generated in the CHP unit. This is due to the substantial difference between import and export prices for electricity. A control system is therefore being developed which will match generation to consumption periods as closely as possible, as well as minimising stop/start cycles and optimising thermal output. Extensive simulation work is being undertaken to evaluate the benefits of optimisation and to ensure that the CHP unit, together with its auxiliary flow boiler can meet the heat demands of the home economically.

The installations will be comprehensively monitored during a twelve month period to assess the effect of summer and winter thermal and electrical load profiles.

PROGRESS SO FAR

The original THERMIE project was planned to cover three years. The first year for the engine modifications, the second for comprehensive laboratory testing and the third for field trials. The engine modifications have been completed and initial laboratory tests indicate that the electrical output will be broadly in line with predictions.

NOTE:

A SUPPLEMENTARY SECTION WILL BE INCLUDED AT THIS POINT TO DESCRIBE THE SIMULATION STUDIES UNDERTAKEN AND ANY DATA FORTHCOMING PRIOR TO PRESENTATION OF PAPER.

ILLUSTRATIONS attached as files

1 CROSS SECTION OF TEM SCP 1-75 STIRLING ENGINE

2 ELECTRICAL LOAD AND GENERATION PROFILES OF TYPICAL UK HOME

3 ECONOMICS OF MICRO CHP

4 SCHEMATIC INSTALLATION DIAGRAM OF MICRO CHP SYSTEM IN HOME