Rapport SGC 144

Demonstration Stirling Engine based Micro-CHP with ultra-low emissions

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FOREWORD

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Johan Rietz

SUMMARY

This project has been initiated in order to develop a new type of natural gas fired low emission combustion system for a Stirling engine CHP-unit, and to demonstrate and evaluate the unit with the newly developed combustion system in a CHP application. The Stirling engine technology is well developed, but mostly used in special applications and CHP-applications are scarce. The very low exhaust emissions with the new combustion system would make the Stirling engine very suitable for installation in as a CHP-unit in domestic areas.

The Stirling engine used in the project has been a V161 engine produced by Solo Kleinmotoren GmbH in Sindelfingen. The unit has a nominal output of 7,5 kW_{EL} and 20 kW_{Heat} (Hot water).

The new combustion system was developed at Lund University and the very strict emission targets that were set up could be achieved, both in the laboratory tests and during the site-testing period. Typical performance and emission figures measured at the site installation are displayed in the table below:

Generator output (kW):	7,3
Hot water output (kW):	15
El. efficiency (%):	25,4
Total efficiency (%):	77,8
NO_x (ppm):	14
CO (ppm):	112
HC (ppm):	< 1
O_2 (%):	8,0
Noise level 1 m from the unit (dBA):	83

(Emission data are measured as % or ppm_{Vol} dry gas)

The NO_x emissions were reduced with almost 97 % as compared to a standard Stirling combustion system. The emission figures are considerably lower than what could be achieved in an internal combustion engine of similar size with an oxidation catalyst (report SGC 106), while the performance figures are similar for the two technologies.

The site testing was carried out during a period of 1½ year at a site owned by Göteborg Energi. The site comprises a building structure with workshops, offices etc. covering a ground area of 2 500 m^2. A gas fired boiler with an output of 250 kW supplies hot water to a local grid for heating and tap water. The annual heat demand is typically 285 MWh and the hot water temperatures are normally 60-80 °C.

The site tests in Gothenburg were not quite successful in the respect that the number of accumulated operating hours, 2 100, was far below the expected. The unit normally also had to be operated at part load. However, this was not due to problems with the Stirling CHP-unit, but mostly was a consequence of “external” factors not actually related to the technology itself.

Many problems, especially during the first months of operation, were caused by interference between the existing external control system for the hot water system and gas fired boiler and the internal Stirling control system, which resulted in frequent shut-down of the Stirling unit. Some problems were also experienced by the internal control system causing shutdowns without any detectable reasons.

When the unit was in operation, it performed well and emission and performance data were quite satisfying. No problems were experienced with the new type of combustion system, which operated very well, although a minor modification had to be made. Some minor modifications should also be done to the internal control system in order to make it easier to handle. The “external” problems mentioned above could easily be solved in a commercial installation.

The feasibility study shows that the market conditions in Sweden for this type of “micro CHP-units” presently isn’t too prosperous. This is mainly due to the rather high investment cost and low electricity prices in Sweden, but the situation in other parts of Europe is probably a lot better in the later respect.

The investment cost including installation is approxemately 270 kSEK (30 kEUR) and the cost for the electricity produced is abt 1,5 SEK/kWh_{EL} (0,16 EUR/kW_{EL}). (6 % intrest, 10 years depretiation, gas price 480 SEK/MWh – 52 EUR/MWh.) This is comparable to other micro-CHP technologies.

The short operating time, mostly on part load, on site limitates the conclusions that can be made on the long-time avaliability and maintenance costs of the Stirling CHP-unit. However, it seems that the low emission Stirling CHP-technology demonstrated is about to be ready for a commercial introduction on the market, once the market conditions become more favourable.

SAMMANFATTNING

Projektets syfte har varit att dels utveckla en ny naturgaseldad lågemissionsbrännkammare för en Stirlingmotorbaserad kraftvärmeenhet, dels att göra en långtidsutvärdering av dennas egenskaper i en fältinstallation. Stirlingmotortekniken är väl utvecklad, men används huvudsakligen i specialapplikationer, t.ex. i u-båtar. Kraftvärmeapplikationer är däremot sällsynta och erfarenheter av sådana saknas helt i Sverige. Stirlingmotorn har goda tekniska förutsättningar för att användas för kraftvärme och de mycket låga emissionsnivåer som uppnåtts i detta projekt gör tekniken väl lämpad för användning i bostadsområden.

Stirlingmotorn som använts i detta projekt är av typ V161, tillverkad av det tyska bolaget SOLO Kleinmotoren GmbH i Sindelfingen. Motorn har en nominell effekt på 7,5 kW_{EL} och 20 $kW_{Värme}$.

Den nya lågemissionsbrännkammaren har utvecklats vid institutionen för förbränningsmotorteknik vid Lunds Tekniska Högskola och de mycket låga emissionsnivåer som sattes som mål vid projektstarten har också kunnat uppnås, både i laboratoriemiljö och vid de praktiska fältförsöken. Typiska prestanda och emissionsnivåer från fältproven redovisas nedan:

Generatoreffekt (kW):	7,3
Hetvatteneffekt (kW):	15
Elverkningsgrad (%):	25,4
Totalverkningsgrad (%):	77,8
NO_X (ppm):	14
CO (ppm):	112
HC (ppm):	< 1
O_2 (%):	8,0
Ljudnivå 1 m från motorn (dBA):	83

(Emissionsdata angivna som % or ppm_{Vol} torr gas)

De uppnådda NO_x-nivåerna är i storleksordningen 97 % lägre än motsvarande nivå för en konventionell Stirlingbrännkammare. Nivån är också avsevärt lägre än vad som redovisats i rapporten SGC 106, där fältförsök gjordes med en förbränningsmotor i samma effektklass försedd med oxidationskatalysator. Övriga prestanda var ungefär likvärdiga.

Fältförsöken pågick under 1 ½ år i en anläggning ägd av Göteborgs Energi. Anläggningen utgörs av en verkstads- och kontorsbyggnad med en yta på 2 500 m^2. Anläggningen har ett lokalt hetvattennät för uppvärmning och tappvarmvatten som försörjs av en naturgaseldad hetvattenpanna på 250 kW. Värmebehovet ligger normalt på ca 285 MWh per år och temperaturnivåerna i nätet ligger i området 60-80°C.

Fältproven i Göteborg utföll inte helt som planerat, då den totala drifttiden blev förhållandevis begränsad, ca 2 100 timmar. Motorn fick också köras på dellast under större delen av provtiden. Detta berodde dock inte i första hand på Stirlingmotorn, utan hade huvudsakligen ”externa” orsaker.

Många driftavbrott, speciellt under de första månadernas drift berodde på dålig samfunktion mellan Stirlingmotorns interna styrsystem och det befintliga styrsystemet för hetvattennät och gaspanna.

Stirlingmotorn fungerade emellertid väl under den drifttid som ackumulerades och uppvisade under drift goda prestanda och emissionsdata. Den nya lågemissionsbrännkammaren fungerade också väl, även om en mindre modifiering fick göras. Några smärre modifieringar av det interna styrsystemet bör också göras, bl.a. för att förbättra användarvänligheten.

En ekonomisk utvärdering av Stirlingteknikens möjligheter på den svenska marknaden har också gjorts och denna visar att marknadsförutsättningarna för såväl Stirlingtekniken som för mikrokraftvärme generellt är ganska begränsade. Detta beror huvudsakligen på att investeringskostnaden är förhållandevis hög, samtidigt som elpriset i Sverige är förhållandevis lågt. Elpriserna i andra delar av Europa ökar sannolikt Stirlingteknikens konkurrenskraft.

Investeringskostnaden för en färdig installation ligger på 270 kSEK och den producerade elen kostar ca 1,5 SEK/kWh$_{EL}$, (6 % r:a, 10 års avskrivning och ett gaspris på 480 SEK/MWh.) vilket är i ungefär samma storleksordning som för andra typer av mikrokraftvärmetekniker.

Den begränsade drifttiden, huvudsakligen på dellast, under fältförsöken gör det svårt att dra några säkra slutsatser tillgänglighet och underhållskostnader.

Sammanfattningsvis tyder dock erfarenheterna på att Stirlingmotortekniken såsom den demonstrerats här i stort sett förefaller vara tekniskt mogen för kommersiell introduktion på marknaden, men att de nuvarande ekonomiska förutsättningarna i Sverige ännu inte medger detta.

Contents

Enclosures

Encl. 1: M. Pålsson, Dept. of Heat & Power Engineering, Lund University
Development of a LPP CGR Combustion System with Ultra-Low Emissions for a SOLO161 Stirling Engine based Micro-CHP unit.

Encl. 2: M Pålsson, Dept. of Heat & Power Engineering, Lund University
Development and Field Test of a SOLO 161 Stirling Engine based Micro-CHP unit with Ultra-Low Emissions.

1 Introduction

1.1 General

The Stirling engine technology has been developed over several years and a number of different models and sized are available, mostly in special applications, for instance as solar driven power generators, submarine power systems etc. The Stirling engine technology also has a potential for use as small-scale decentralised combined heat and power units. Amongst the benefits of the Stirling technology that are desirable for small scale CHP-units are:

- High electrical efficiency
- High overall efficiency
- Low noise levels
- Relatively low exhaust emission levels
- Good part load characteristics

However, Stirling engine units in CHP applications are relatively scarce and these are more or less prototypes or development units. The main back-draw could be a less well-known technology and a relatively high cost per unit. The former probably considered as being high-tech and unfamiliar to the general public. The latter since the low-cost benefits of mass production not yet are available due to the low market demand, which prevents mass production etc.

In the recent years, the interest for decentralised combined heat and power production has increased and this would make an opportunity for a break-through for the Stirling engine technology in this application. Especially as CHP-units in public buildings, apartment blocks etc., where the heat demand is in the range from 5-50 kW.

This project has been initiated in order to develop a new type of natural gas fired low emission combustion system for a SOLO Kleinmotoren V161 Stirling engine CHP-unit, and to demonstrate and evaluate the unit with the newly developed combustion system in a CHP application. The very low exhaust emission with the new combustion system makes the Stirling engine very suitable for installation in domestic areas.

The project, Demonstration – Stirling Engine Based Micro-CHP with ultra-low emissions, was started in January 1999 and was planned to have duration of three years. However, a number of problems of both technical and administrative nature, made it necessary to prolong the project with almost two years in order to get a reasonable number of operating hours of the Stirling engine unit.

1.2 Project targets

The purpose of the project has been:

- Design and testing of a combustion system for natural gas with extremely low exhaust emission levels.
- Demonstration and evaluation of the operation of a Stirling engine CHP unit equipped with the new combustion system.

The Stirling engine used in the project has been a V161 engine produced by Solo Kleinmotoren GmbH in Sindelfingen, Germany. The unit has a nominal output of 7,5 kW_{EL} and 20 kW_{Heat} (Hot Water).

The ultra-low emission combustion system was developed by LTH (Lund Technical University). The target values for the new combustion system and data for the "conventional" combustion system are found in the table below:

	Target values New Combustion system	"Conventional" Combustion system
NO_X (ppm)	< 10	220-650
HC (ppm)	< 1	< 1
CO (ppm)	30-50	150-800

All data at 5 % O_2

The reduction of NO_x has been the main target and as can be seen from the table above, the target value corresponds to a reduction in the region of 97-98 %.

The evaluation of the unit includes parameters such as:

- Performance
- Emission levels
- Reliability
- Maintenance costs
- Operating costs
- General operating experiences

The evaluation also includes a short feasibility study describing the market potential for the Stirling CHP technology in Sweden.

1.3 Project partners

The project is administrated by Svenskt Gastekniskt Center AB, SGC.

The following partners have taken an active role in the project work with main responsibilities as mentioned below:

- Gothenburg Energy: Project management, site installation of the unit.
- Lund University, Division of Combustion Engines: Combustor system development, measurements in laboratory.
- INTERSOL: Heater system, installation, operating assistance and maintenance.
- SOLO Kleinmotoren: Supply of Stirling engine unit.
- Carl Bro Energikonsult AB: Emission measurements on site, evaluation programme and reporting.

The project has been financed by:

- STEM
- Gothenburg Energy
- Lund University (LTH)
- Sydkraft/Sydkraft Gas
- Intersol/SOLO Kleinmotoren
- Energie Ned
- Danish Gas Technology Center
- NOVA Naturgas
- Fortum Värme
- Öresundskraft
- Lund Energy

1.4 Project implementation

The project has had a duration of more than four years and a brief view of the project progress and main activities during this time is given below.

1999:

- Project start
- Identification of a suitable test site – Local boiler station in Gothenburg supplying heat to a combined office, workshop and warehouse owned by Gothenburg Energy
- Manufacturing of the V161 Stirling Engine at SOLO Kleinmotoren
- Development, design and testing of the combustion system in the LTH laboratory on an existing V160 Stirling Engine
- Delivery of the V161 Stirling Engine to LTH for further combustion system testing

2000:

- Continued development work and testing with the V161 engine at LTH
- Design and preparation of the site for the installation of the V161 unit in Gothenburg
- Final tests and emission measurements in the LTH laboratory
- Installation of the V161 unit at the site in Gotenburg (November)
- First start of the V161 unit on site (2000-12-13)

2001:

- Administrative work in order to get necessary approvals for the natural gas installation
- 2001-02-11 Start of the site operation
- Work on data acquisition system and the control interface between the engine control system and the “district heating” control system
- 2001-10-16 Emission and performance measurements # 1
- 2001-12 Engine stopped and dismantled for overhaul and repair
- A total of about 1400 hours of operation was achieved during 2001

2002:

- Continued overhaul and repair during the first three months
- Site operation continued from 2002-03-18 to 2003-07-04
- 2002-05-07 Emission and performance measurements # 2
- 2002-07-03 Emission and performance measurements #3
- 2002-07-04 End of site operation
- Evaluation of site tests
- A total of about 700 hours of operation was achieved during 2002

2003:

- V161 unit moved from the site in Gothenburg to LTH
- Evaluation and final reporting of the project

2 Stirling Engine Technology

2.1 Stirling engine working principles

The Stirling engine is a reciprocating engine with pistons working in cylinders and the linear movement of the pistons is transferred to a rotating movement on a crankshaft via piston rod, crosshead and connecting rod in the same manner as a conventional Otto or Diesel engine. The main difference between the Stirling engine and the Otto/Diesel engines is the combustion cycle.

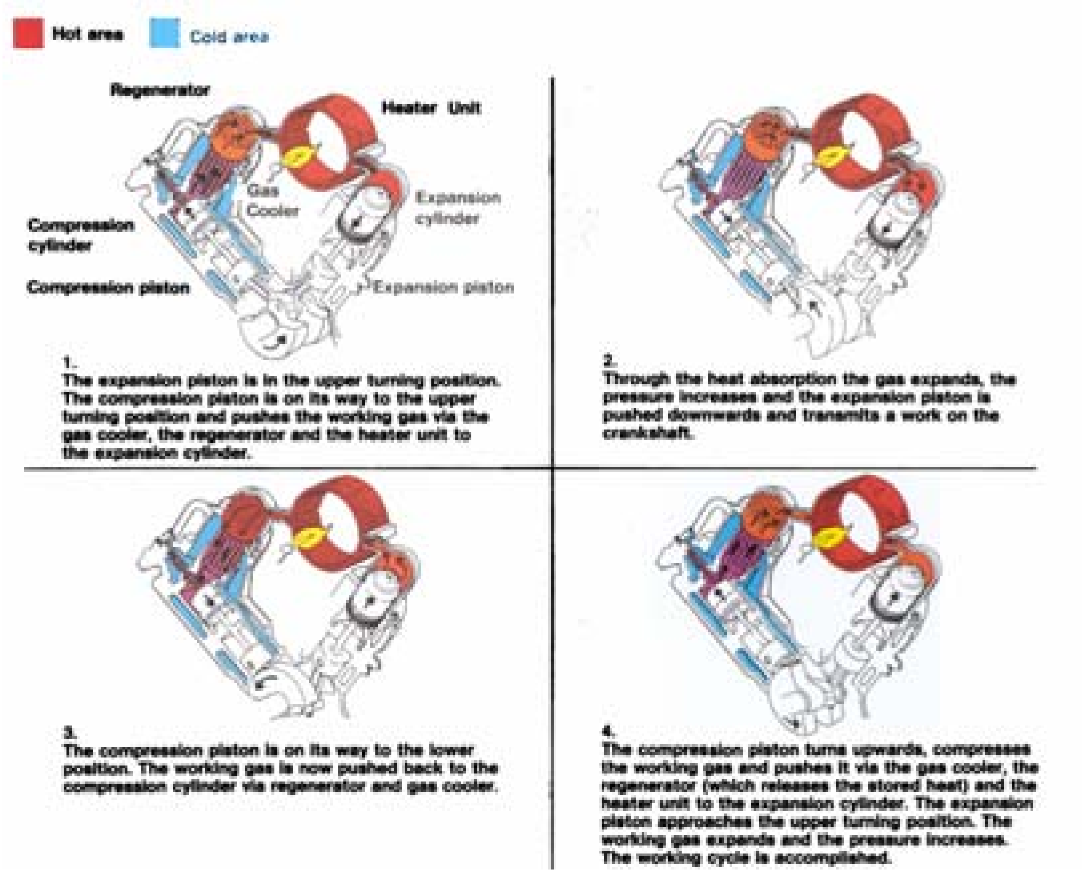
The Otto and Diesel engines are internal combustion engines, where a mixture of combustion air and fuel are ignited and combusted inside the cylinder and exposing the cylinder walls and piston rings to residual deposits from the combustion etc.

The Stirling engine differs from the working principle above, as the fuel is combusted in an external combustion system and the heat from the combustion is transferred to the working media in the cylinders via a heat exchanger. The combustion in the Stirling engine combustion system is a continuous process with a steady flame as in a conventional boiler, while the combustion process in the internal combustion engine is cyclic, with a short rapid combustion during a part of the process cycle.

The working media in a Stirling engine is kept in a closed loop and isn't exchanged between cycles. Different types of gases can be used as working media, for instance air, hydrogen or helium. Hydrogen has the best properties from a thermodynamically point of view, but it has the disadvantage of being highly flammable and hazardous to use in normal applications. Therefore, helium is normally used, since it is an inert gas and has good thermal and aerodynamic properties.

Since the combustion process takes place outside of the cylinders in the separate combustion system, it is virtually possible to use all types of fuels to generate heat for the Stirling engine process, assuming that the combustion system and heat exchanger are designed for the type of fuel in question. The combustion system and the heat exchanger are normally referred to as the "heater unit". Even if Stirling engines normally are designed for gas- or liquid fuels, designs have been made for solid biomass fuels as well as for "sun-heated" engines, where a dish-mirror focuses sunbeams in to the Stirling engine heat exchanger.

It should be noted that Stirling engines have been manufactured in a wide variety of designs, cylinder numbers, layout, etc., but the working principles as described below are general for the Stirling cycle, independent of the type and manufacture:



The helium pressure in the cycle controls the engine output. The helium is stored in a separate storage tank and the helium pressure in the cycle can be adjusted by a small pump and valve system that transfers helium between the storage tank and the cycle. When the engine output is to be increased, helium is transferred from the storage bottle to the Stirling engine, thereby increasing the cycle pressure. When the engine output is to be decreased, helium is pumped back from the engine to the storage bottle. The control system keeps the helium temperature at a constant level of about 650 ^{o}C independent of the engine load by adjusting the fuel- and airflow to the combustion system.

The heater unit is one of the key components in the Stirling engine, being technically advanced due to the requirements of good heat transfer properties, high operating temperature (600-700 ^{o}C) and high operating pressure (10-15 MPa), which makes it necessary to use high tech materials and manufacturing methods for the heat exchanger.

The Stirling engine has two heat sources that can be used for hot water production in a CHP-application. Most of the heat is produced in the gas cooler that cools the helium in the Stirling cycle, while additional heat can be generated by a heat exchanger installed in the exhaust gas pipe.

2.2 Stirling engine applications and manufacturers

Stirling engines have been manufactured for different applications with outputs ranging from < 1 W up to 150 kW. Due to the high manufacturing costs, Stirling engines are normally used in special applications where the investment cost is of secondary importance. One exception is the SOLO V161 Stirling engine, which is commercially available as a CHP-unit.

Stirling engine technology development and research is also carried out at universities, such examples being Lund University within this project, and the Technical University of Denmark. In the Danish University work has been focussed on a 4-cylinder engine with an output of 35 kW_{EL} with a combustion system designed for solid bio-mass fuels.

Stirling engine with bio-mass heater on top in the laboratory of the Technical University of Denmark

Another example of a "commercial" manufacturer of Stirling engines is STM Power Inc. in USA, who is marketing CHP-units with an output of 25 kW_{EL} and 44 kW_{Heat}. The president of the STM Power Inc. is originally from Sweden and has formerly been working at another well-established Stirling engine manufacturer, Kockums in Sweden, who are producing Stirling engines for military purposes. The Kockums engine has an output of about 75 kW and is used in submarines as an "air-independent" propulsion unit that prolongs the underwater operation of a submarine with several weeks as compared to conventional diesel electric propulsion.

2.3 The SOLO Kleinmotoren V161 Stirling engine

The SOLO V161 Stirling engine originates from a Swedish design, i.e. the V160 Stirling engine, which was developed in the mid 1970 by the Swedish company United Stirling and later by FFV (United Defence Works). The V160 engine had an output of 6 kW_{EL} and the same principal design as the present V161 engine. The development was later transferred to the American company Stirling Power Systems.

The V160 engine has been built in a number of versions, and a total of 158 V160 engines have been produced. These engines have accumulated about 400 000 running hours. The Swedish Televerket has used some V160 units as mobile generator sets. Other units have been adopted for use in solar applications, where a dish mirror, which focuses the sunbeams into the Stirling engine heater unit, is used for heating the helium in the Stirling cycle.

Sandia- WGA- Dish/Stirling-System in Albuquerque, USA

In 1989 the German company Schlaich, Bergmann & Partner bought a license from Stirling Power Systems and the manufacturing license was transferred to SOLO Kleinmotoren GmbH and the concept with solar dish Stirling engines was developed further and more than 40 000 hours of operating time have been accumulated by these units.

The V161 Stirling engine unit is a modification of the V160 unit, where the modifications mainly have been focussed on reduction of production costs and improving the availability of the engine. The V161 engine was taken into production in 1994, the design being a corporation between SOLO and Intersol. Until now, approximately 20 V161 Stirling engines have been delivered, of which 6 are solar dish units.

The SOLO V 161 engine has two cylinders in V-formation, a compression- and an expansion-cylinder in which the working gas is moved in a closed thermodynamic cycle. Inside the compression-cylinder the gas is isothermally compressed at a low temperature level by cooling with water, then it is moved through the regenerator, where it is heated up to 650 °C, to the expansion-cylinder. During the isothermal expansion the gas is heated by the heater, afterwards the gas is moved back through the regenerator, where it is cooled down, to the compression cylinder. The heater consists of small tubes which are heated up to approx. 700 °C from the outside by a burner. The working gas cooler is a small heat exchanger cooled by water. The regenerator is a compressed metal fabric screen being a thermal storage during the cycle. The exhaust gases are leaving the combustion system with a temperature of approx. 800 °C. To reach a good efficiency, the thermal energy has to be transferred to the combustion air by an air preheater, where the air is heated up to 600 °C. The exhaust gases are cooled down to about 250 ^{o}C before leaving the air preheater.

The piston rods are connected to the crankshaft by connecting rods, the dry-running pistons in the high pressure chambers are sealed against the oil-lubricated crankcase by (especially developed material) piston seals.

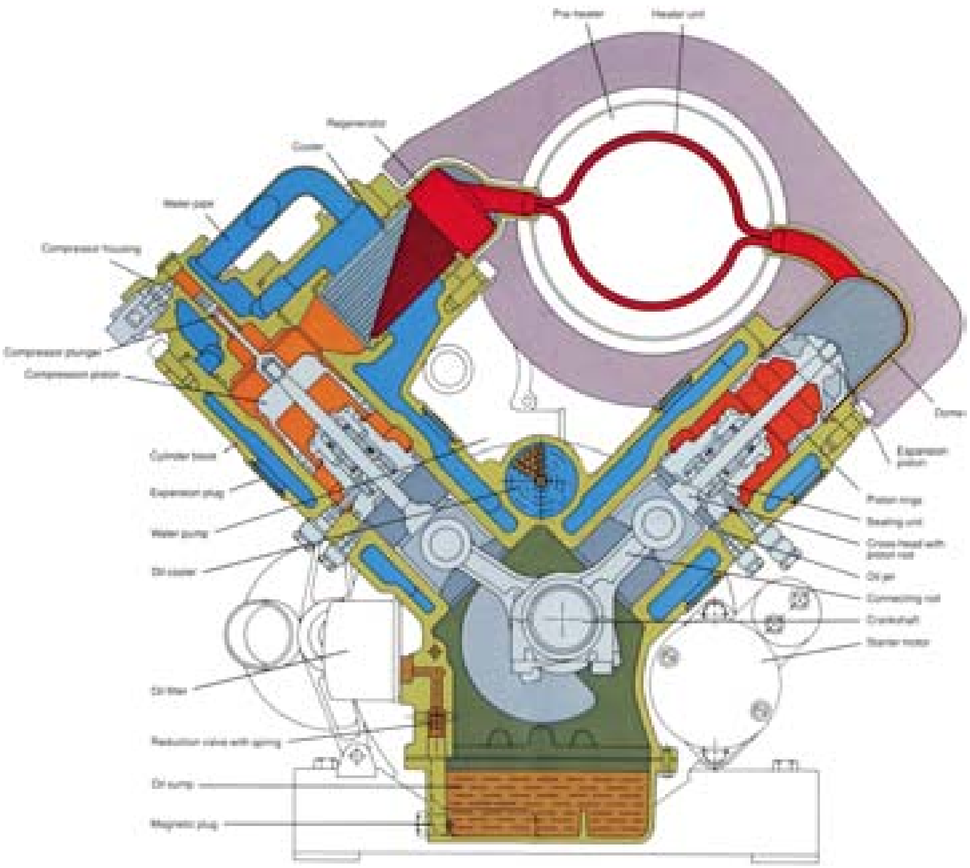
The combustion is continuous, and not cyclic as in an internal combustion engine, which improves the possibilities to control the combustion process, thereby making it possible to reach very low emission levels without any after treatment of the exhaust gases.

The V161 Stirling engine has the following main data when operating as a CHP-unit:

Engine type:	V 2-cylinder
Bore:	68 mm
Stroke:	44 mm
Total cylinder volume:	160 cm^3
Rotational speed:	1500 rpm
Nominal electric output:	7,5 kW
Max. electric output:	9 kW
Nominal heat output:	23 kW
Maximum cycle pressure:	15 MPa
Maximum cycle temperature:	650 ^{o}C
El. efficiency:	24 %
Total efficiency:	90 %

The output and efficiency figures are nominal figures at cooling water inlet temperature 50 ^{o}C. Actual figures are depending on the cooling water temperature and the engine performance decreases with increasing cooling water temperature, see 2.4.

The Stirling engine is directly connected to a 3-phase asynchronous generator with a voltage of 0,4 kV. This makes the connection to the grid fairly simple and the generator is also used as motor for starting up the Stirling engine.



Cross section of the V160 Stirling engine

A gas supply pressure of 50 mbar is sufficient for the engine control system. This pressure is generally available at all conceivable installation sites in Sweden.

2.4 The V161 Stirling engine as a CHP-unit

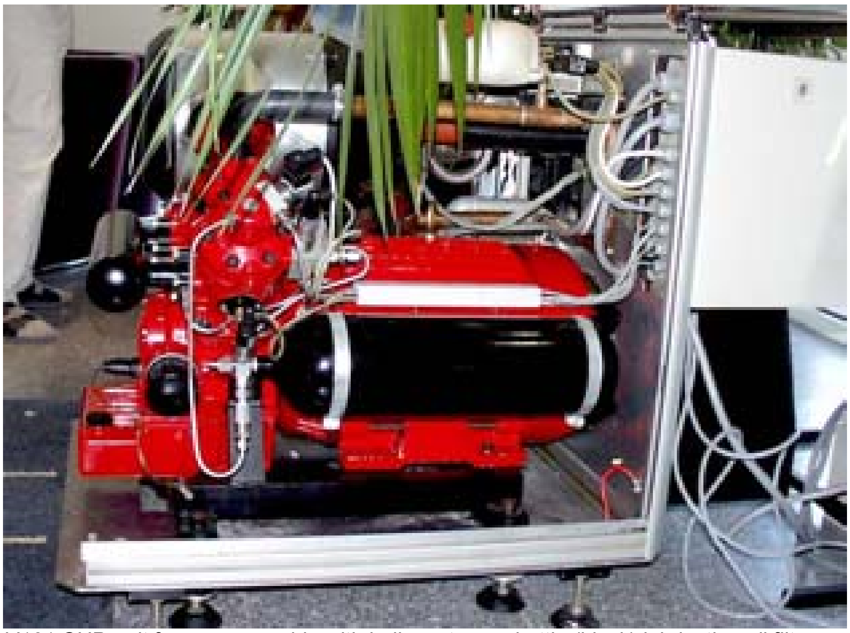
The V161 CHP-unit is delivered as a “turn-key” unit with built-in control & safety system, data collection system with a modem that monitors relevant engine parameters for diagnostic purposes, cooling water system etc. The unit is assembled on a frame with a sound insulated hood. The standard unit is equipped with a “low-NO_x” type combustion system, with a large proportion of exhaust gas-recirculation, which is called “flameless oxidation” (Flox®-Operation). With the Flox® combustion system NO_x-emissions are approximately five times higher than the levels achieved with the combustion system that has been developed within the scope of this project.

The main dimensions of the CHP-unit are; (LxWxH) 1,35 x 0,7 x 1,0 m. The total weight of the unit is 450 kg.

SOLO V161 CHP-unit on display at Sydkraft head office in Malmö prior to installation in Gothenburg

All connections for gas fuel, cooling water, exhaust gas and electricity are assembled on the rear end of the unit, which facilitates the installation and maintenance of the unit. During maintenance, the hood can easily be folded back, giving full access to the unit.

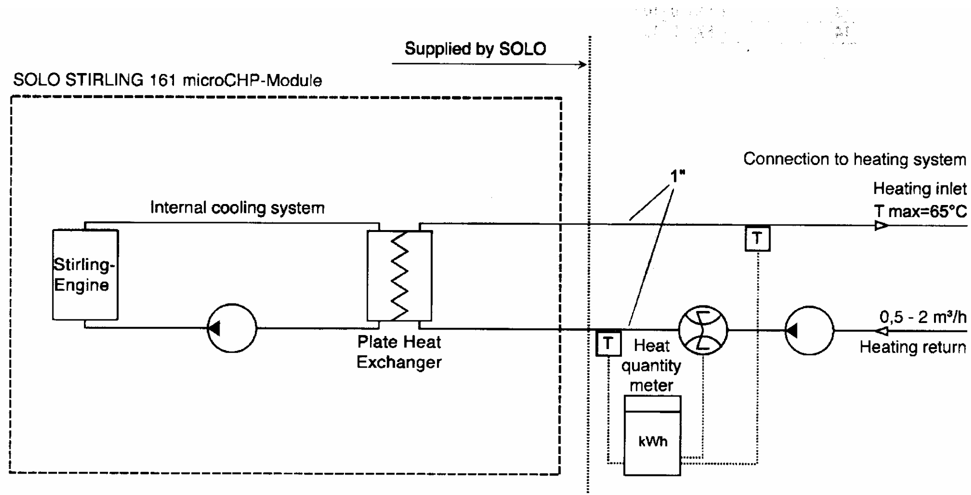
V161 CHP-unit with hood folded back showing; heater unit (grey), Stirling engine (below heater unit), generator, cooling water plate heat exchange and internal cooling water pump.



V161 CHP-unit from reverse side with helium storage bottle (black) lubricating oil filter, control cabinet etc.

As mentioned earlier, the Stirling engine has two heat sources that can be utilised for hot water production in a CHP-application. The main heat source is the helium gas cooler that cools the helium gas in the cold end of the cycle. Additional heat can be produced if a heat exchanger is installed in the exhaust gas pipe. The latter increases the heat output with approximately 10 %.

The CHP-unit has an internal cooling water system with a circulation pump and the heat is transferred to the external water system via a plate heat exchanger.

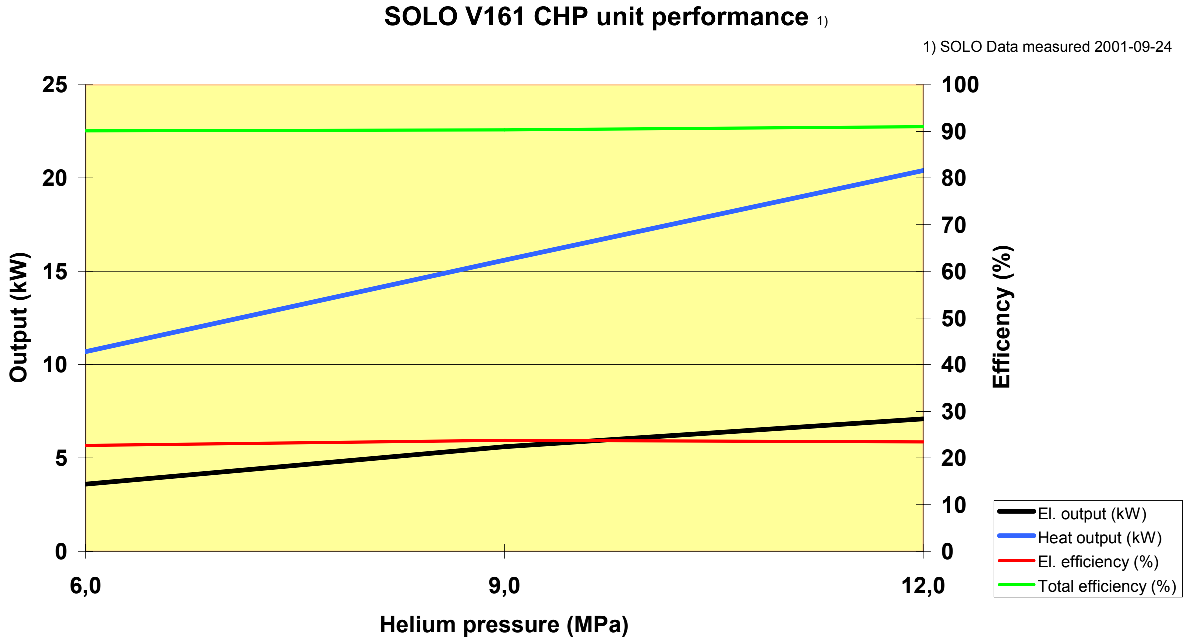


Cooling water system layout

Typical V161 CHP-data at a helium cycle pressure of 12 MPa are found in the table below[1]:

El output (kW):	7,1
Hot water output (kW):	20,4
Gas fuel input (kW):	30,2
El efficiency (%):	23
Heat efficiency (%):	68
Total efficiency (%):	91
Exhaust gas flow (kg/s):	0,014
Exhaust gas temp. after heat exchanger (°C):	63
Hot water inlet temp. (°C):	44

It should be noted that the data above are actual data measured at a CHP installation in Germany and that engine output and efficiency are depending on cooling water temperature. An inlet temperature increase of 10 °C will give a reduction of the el. output by 0,5 kW and a reduction of the el. efficiency by 1 %-unit. If the V161 engine is operated for el. production only (i.e. no hot water production), the cooling water temperature can be reduced down to 10-20 °C, which increases the el. output to about 9 kW and the el. efficiency by 2,5 %-units.



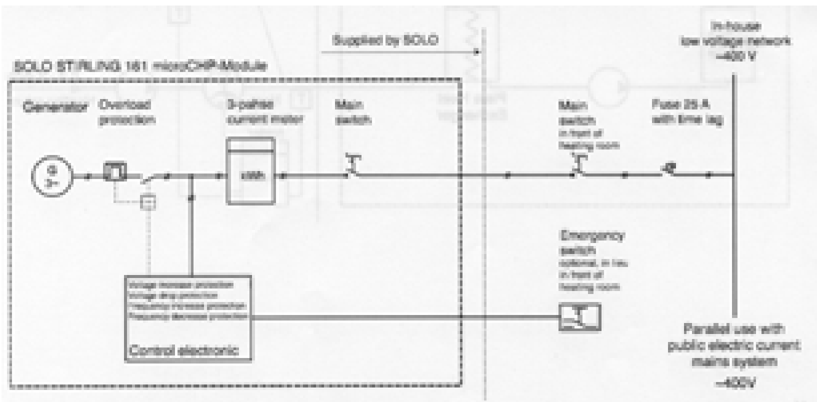
Both the electrical and total efficiency figures can be kept fairly unaffected at part load operation down to about 50 % engine load, as can be seen in the diagram below. The data have the same origin as the data at 12,0 MPa above. At part load below 50 %, the efficiency figures will show a slight decrease.

The V161 unit can be operated down to a minimum load of about 2 kW_{EL}, giving an operating range from 25 to 100 % el. output.

[1] SOLO Kleinmotoren V161 engine data measured 2001-09-24

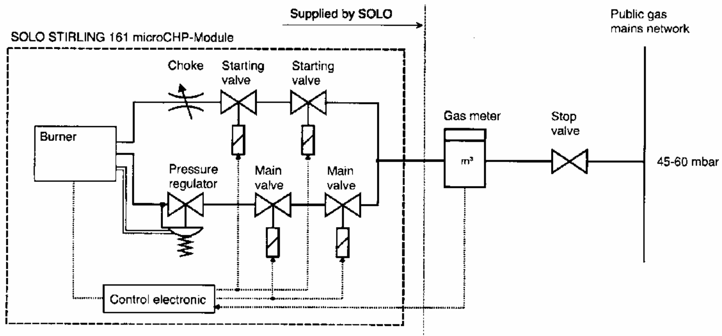
The maximum cooling water inlet temperature is restricted to 60 ^{o}C and the maximum outlet temperature is in the range 65-70 ^{o}C. The temperature levels in Swedish district heating systems are normally in the range 50-90 ^{o}C, but the systems are designed for a maximum temperature of 120 ^{o}C, which is necessary during the coldest wintertime periods. This prevents the use of the Stirling technology in conventional district heating systems. In stead, the Stirling technology can be used in “local heating applications”, such as public buildings, apartment blocks etc., where 65-70 ^{o}C is quite sufficient for heating of buildings and tap hot-water. Normally, a conventional hot-water boiler for use as stand-by and peak-shaving unit should support the Stirling engine. In order to get optimum operating conditions and economical outcome for the Stirling unit, the heat output from the Stirling unit should be approximately 30 % of the maximum heat demand in the system. This corresponds to about 50 % of the annual energy demand in the system being produced by the Stirling unit. If a hot water accumulator tank also is installed in the system the annual production share of the Stirling unit can be increased, since the accumulator tank will be able to take care of minor variations of the heat demand in the system.

The connection of the V161 CHP-unit to the electrical grid is relatively uncomplicated as the generator is of the asynchronous type, which makes the electronic control system quite simple as indicated in the diagram below. It should be noted that the actual layout is depending on the local conditions and connection to the grid. Normally two electric meters will be required, one measuring the kWh produced to the grid and one measuring the kWh consumed if the CHP-unit is out of operation. The unit also uses some electricity during the start up phase as the asynchronous generator also is used as starting motor.



Electrical connection

The connection to the main gas network is simplified since all necessary equipment, apart from the gas meter, is included in the V161 CHP-unit.



Gas connection

The exhaust gas leaving the exhaust gas heat exchanger has a temperature below 100 ^{o}C, which means that the heat exchanger has to be connected to water drainage, where condensate from the exhaust gas can be disposed of.

The V161 CHP-unit is equipped for fully automatic operation and can be operated in different control modes, for instance at a preset el. output or by setting a required hot water outlet temperature which controls the engine load. Start and stop are also fully automatic, but the unit should not be shut down and restarted more than once a day, since thermal loads during shut-down and start up affects the wear on engine components which affects maintenance intervals and costs. The starting procedure requires several minutes in order to keep the thermal loading during the heating up sequence to an operating temperature of 700 ^{o}C at acceptable levels.

3 Development of the Ultra Low Emission technology at Lund University

3.1 Background

At Lund University, the Department of Heat & Power Engineering, have a long tradition of research and development work on the Stirling Engine technology. Special attention has been paid to the combustion process, and during the last decade extensive research has been made on lean premix combustion with burnt gas recirculation and a metallic flame holder.

The development work made within the scope of this project was made as a part of a Doctoral Thesis by Magnus Pålsson [1], which was presented in May 2002. The development work, combustion theories and emission measurement are thoroughly described in the Doctoral Thesis.

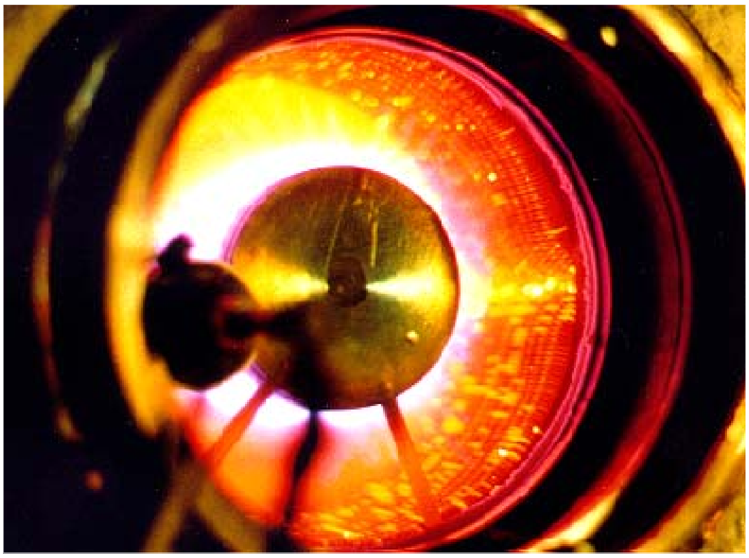
Dr. Pålsson also has summarized the development work in two papers, "Development of a LPP GCR Combustion System with Ultra-Low Emissions for a SOLO 161 Stirling Engine Based Micro-CHP Unit", which is included within this report as Enclosure 1. The second paper, "Development and Field Test of a SOLO 161 Stirling Engine based Micro-CHP unit with Ultra-Low Emissions", is included as Enclosure 2.

3.2 Scope of work

The development work that was made at the Department of Heat and Power Engineering at Lund University is very well described in Enclosure 1. It will therefore only be summarized in this chapter, while the detailed description can be found in Enclosure 1.

The development of the new Ultra-Low emission combustion system has been based upon previous development work at Lund University. The new combustion system is a further development of earlier work on a Stirling V160 combustion system. The target has been to reach the "Ultra-Low" emission levels described in chapter 1 and to adapt the design in order to make it easy to manufacture. Other items that have been addressed within this work has been to investigate start-up and control strategies in order to get a fully operational design ready for field testing under real operating conditions.

The initial testing was started with an experimental combustion system, which was fitted onto a V160F Stirling engine in the laboratory in Lund. The combustion system was fitted with a quarts glass window, which made it possible to get optical assess to the actual combustion process. Based upon the results from these tests, a new combustion system was designed by Intersol. Meanwhile, the SOLO V161 Stirling engine to be used for the field-testing was delivered by SOLO to Lund University, and the new combustion system was installed on this unit for the second phase of the testing.


View of the combustion through the quarts glass during the laboratory tests

A number of test were made and some design modifications had to be made. Extensive work was also made on the control system and air-/gas control valves in order to get the required sophisticated and accurate combustion control, not only at 100 % load, but also in the whole operating range of the system.

The work that had to be made at the Lund University became more comprehensive than originally planned due to “secondary” problems that had to be solved before the engine was ready for the field tests. This made it necessary to prolong the period in Lund with almost a year. Among the “secondary” problems that had to be taken care of were:

- Adaptation of the gas- and air control system from the “high pressure” system used in the laboratory to the 100 mbar pressure used on site in Gothenburg. Among other things, it turned out to be quite difficult to find a gas control valve with suitable characteristics.
- Extensive work had to be put down on the control system, both for normal operation and for the start-up procedure.
- The flame holder in the combustion system had to be redesigned due to a mechanical failure during the tests.

In order to get the engine installed in Gothenburg during the winter/operating period 1999-2000 it was also necessary to make a considerable reduction of the time for tuning in and test operation of the engine in the laboratory as compared to the original time schedule.

After two years of development and test work, the laboratory tests could be finished with the target goals achieved in November 2000, and the unit was transferred to Gothenburg for the field tests.

3.3 Combustion system design

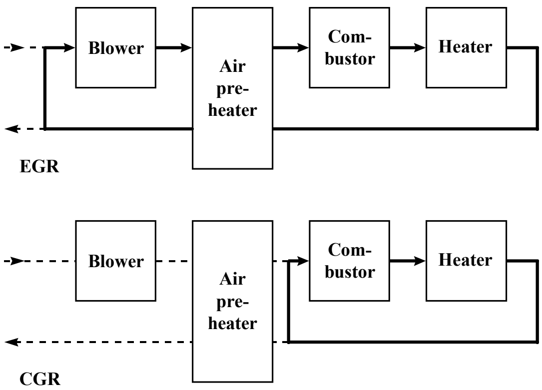
One of the characteristics of the Stirling engine technology is that the exhaust gases leaving the combustion system are used for preheating the combustion air for reasons of efficiency. The air is heated in a heat exchanger to a temperature level of 500-600 ^{o}C while the exhaust gases are cooled down to about 250 ^{o}C.

Since the formation of NO_x is rapidly increased at elevated combustion temperatures, it is essential to keep a “low” flame temperature in the combustion system. The high inlet air temperatures that are necessary in the Stirling cycle offers an extra challenge in the respect of keeping the flame temperature at acceptable levels with regard to NO_x-formation. A number of options for NO_x-control are available. These are briefly described in Encl. 1. The method that has been used by Lund University is recirculation of combustion gases back into the combustion system.

Recirculation of combustion gases increases the mass flow through the combustor. The combustion gases are more or less inert and thereby decrease the oxygen concentration in the combustion system. Both these factors contribute to a considerable reduction of the flame temperature and NO_x-formation.

Two different methods can be used for recirculation of combustion gases, EGR and CGR.

- EGR (Exhaust Gas Recirculation) means that exhaust gases (cooled in the preheater) are recirculated.
- CGR (Combustion Gas Recirculation) means that hot combustion gases are recirculated from after the heater, inside the combuster.

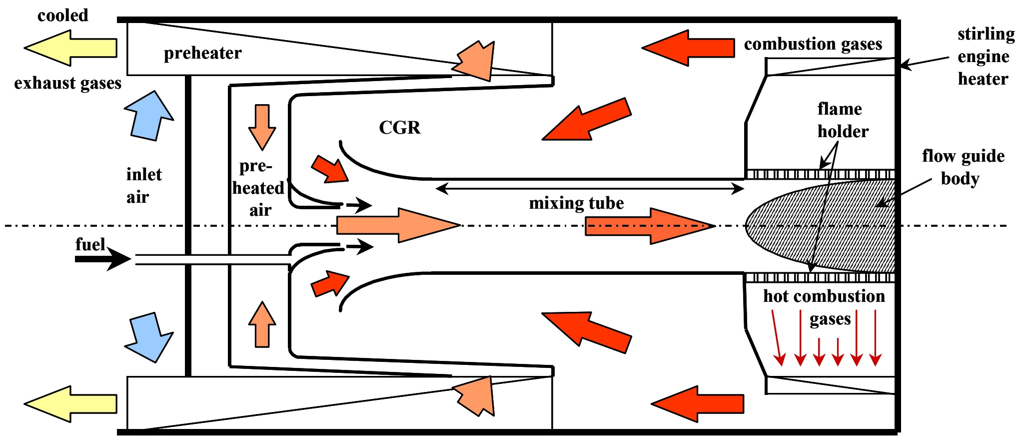


Principles for combustion gas recirculation

The use of EGR will decrease the preheater efficiency, and both EGR and CGR will in varying degrees increase the combustor pressure losses.

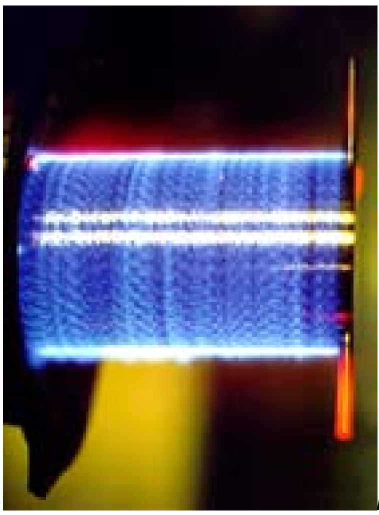
Development work on a V160 combustion system with EGR was initiated at Lund University in the early 1990:s. The results were promising as low NO_x-levels could be achieved, but the system had the drawback of high pressure losses in the combustion system and a reduction of the efficiency in the air preheater.

The research was later continued with the CGR-system, at first by using an electrically driven fan to recirculate the hot combustion gases, which was later abandoned due to the difficulties of operating a fan at the high temperature levels of the combustion gases. In stead, an alternative with an internal ejector was tested out and this solution was adopted for the “Ultra-Low emission” combustion system developed within this project. The ejector is relatively simple to manufacture, once the correct design is found, and has no moving parts, i.e. no reliability or maintenance problems. A schematic view of the final design of the combustion system and main components is found in the picture below.



Final design of the Combustion system used on the V161 CHP unit in Gothenburg

The flame holder is one of the essential components in the combustor as it helps to keep the flame at stable conditions in the flame holder area.


Flame holder with flame in the Laboratory

A comprehensive test program was carried out at the laboratory in Lund. A number of different designs of flame holder and air nozzles were tested until the optimum configuration were found. The test program also included studies of the influence of the amount of CGR in the combustor. Since the actual CGR flow depends on the nozzle geometry, which is fixed, the recirculation flow was varied by a combination of CGR and EGR, where the latter could be varied. The final combustor design has a CGR flow of about 50-60 % of the total exhaust gas flow.

As has been mentioned earlier, special attention was also paid in order to make the combustion system suitable for cheap mass production with high operational reliability without compromising the “Ultra-low” emission levels. Minimizing the use of expensive materials and maximizing the use of easily manufactured sheet material in the design have achieved this.

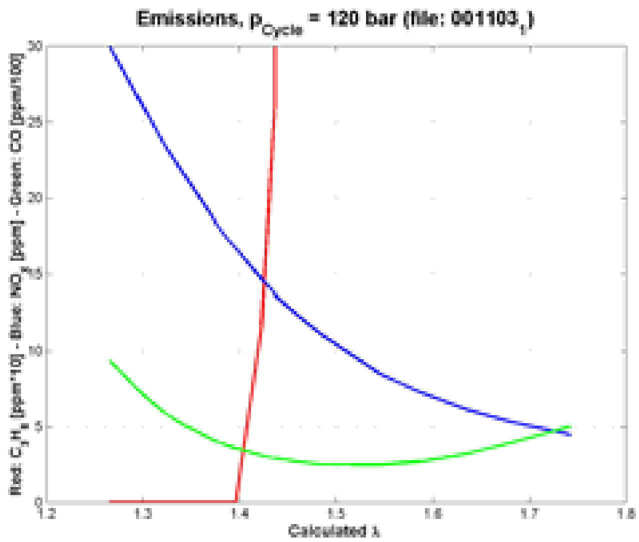
3.4 Emission levels achieved

Finally, but not least, the emission targets that were set up when starting the project were achieved, even if the CO-emission were higher than the target values.

The final results from the laboratory tests are found in the table below:

	Taret values New-Combustion-system	Measured-values Lund University	“Conventional” Combustion-system
NO_x (ppm)	< 10	**15**	220-650
HC (ppm)	< 1	**2**	< 1
CO (ppm)	30-50	**350**	150-800
O_2 (%)	5	**6**	5

The NO_x and HC targets have been reached, but the CO-emissions are significantly higher than the target values. However, this is of minor significance since the measured levels are far below the levels that are considered to present any health hazards or to have any negative environmental influences.



Emission data measured in the Lund University laboratory at varying λ-value at full engine load

The results from the testing in Lund are normally presented as a function of the λ-value (i.e. amount of remaining O_2 in the exhaust gases), at a given cycle pressure. The λ-value gives an indication of the amount of combustion gases that have been recirculated. As can be seen in the graph above, the “optimum” λ-value, to some degree has to be a compromise between the acceptable levels for the different types of emissions as well as other operational factors such as flame stability, stable control and good combustion efficiency.

$$\lambda = 1 + 0{,}90 * \frac{O_2}{(20{,}9 - O_2)}$$

O_2 = Measured $\%_{\text{-dry}}$ in the exhaust gas
0,90 = Correction factor for natural gas fuel

4 Site operation in Gothenburg

4.1 Site description

A suitable location for the field-testing of the CHP-unit was established together with Göteborg Energi, the local utility company in Gothenburg. The site that was chosen was a combined office, workshop and warehouse belonging to Göteborg Energi. The building has a total area of 2500 m^2 and is supplied with hot water for heating and tap water from a natural gas fired boiler with an output of 250 kW. The boiler is installed in a small boiler house located close to the office building. The CHP-unit was installed in the boiler house and all necessary preparations in the hot water-, gas- and electrical systems were made prior to the actual installation was made. All planning and installation work on site was made by Göteborg Energi or their sub-contractors. The installation of the CHP-unit was therefore only a matter of days, once the unit had been transported to the site.

Office & warehouse with boiler house (yellow) on the right

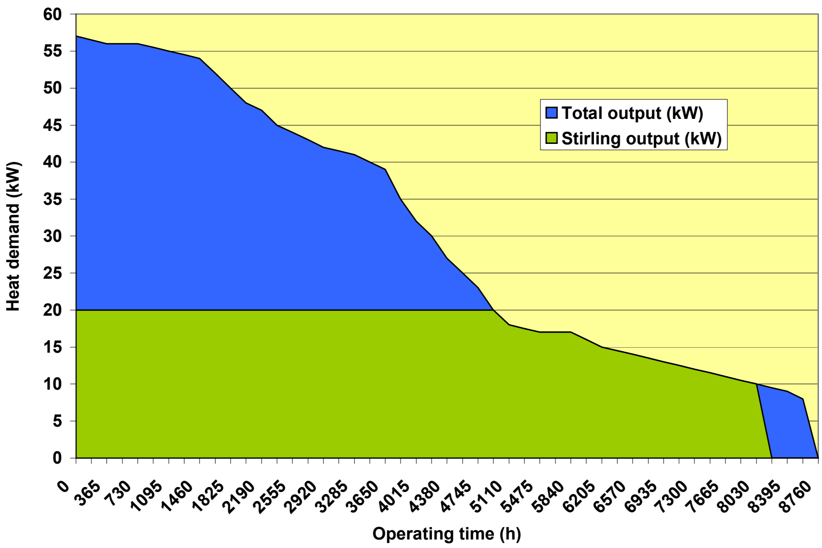
A short exhaust pipe with a length of about 4 m for the CHP-unit was also set up. (Just visible behind the boiler house – compare to the high boiler exhaust pipe in the picture above.)

Stirling engine CHP-unit installed at the site in Gothenburg. Note exhaust pipe (aluminium coated) going through the wall and gas fired boiler (blue)

The annual heat demand in the system is approximately 285 MWh and the variation in the demand during one year (8760 h) is found in the duration graph below. The graph also shows that the Stirling CHP-unit has a theoretical operating time at full load of about 5000 hours and if part load operation down to 50 % heat load is included a total annual operating time of more than 8000 h could be achieved. The Stirling CHP-unit covers about 50 % of the total heat demand in the system.

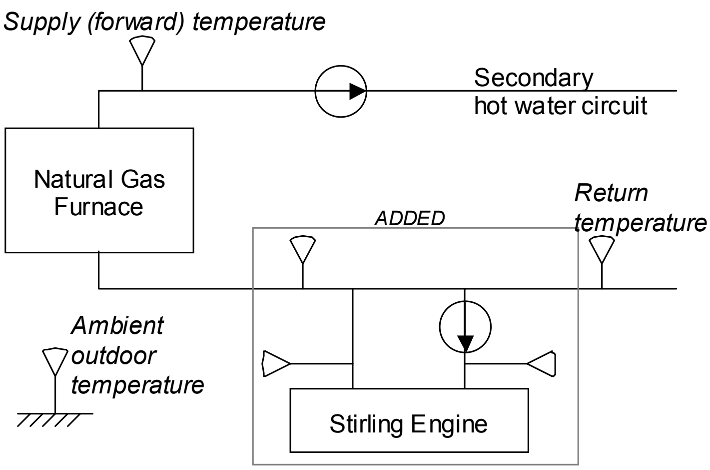
The temperature in the hot water system is normally kept in the region 60-80 ^{o}C. The actual temperature level is adjusted depending on the outdoor temperature with increasing hot-water temperature when the outdoor temperature decreases. At outdoor temperatures above –5^{o}C the supply temperature is normally 65 ^{o}C and the return temperature is about 10 ^{o}C lower. In order to get as favourable working conditions as possible for the Stirling CHP-unit, a slight reduction of the temperatures in the hot water system were made. When higher supply temperatures than 65 ^{o}C were required, the final heating was made in the gas-fired boiler.

Annual heat demand on site (kW)



4.2 Installation

The CHP-unit was installed in the hot water system ahead of the gas-fired boiler. The unit had it's own water circulation pump which drew water from the return hot water pipe and the water was returned to the system ahead of the boiler at the required temperature. A simplified flow diagram of the hot water system is found in the figure below.

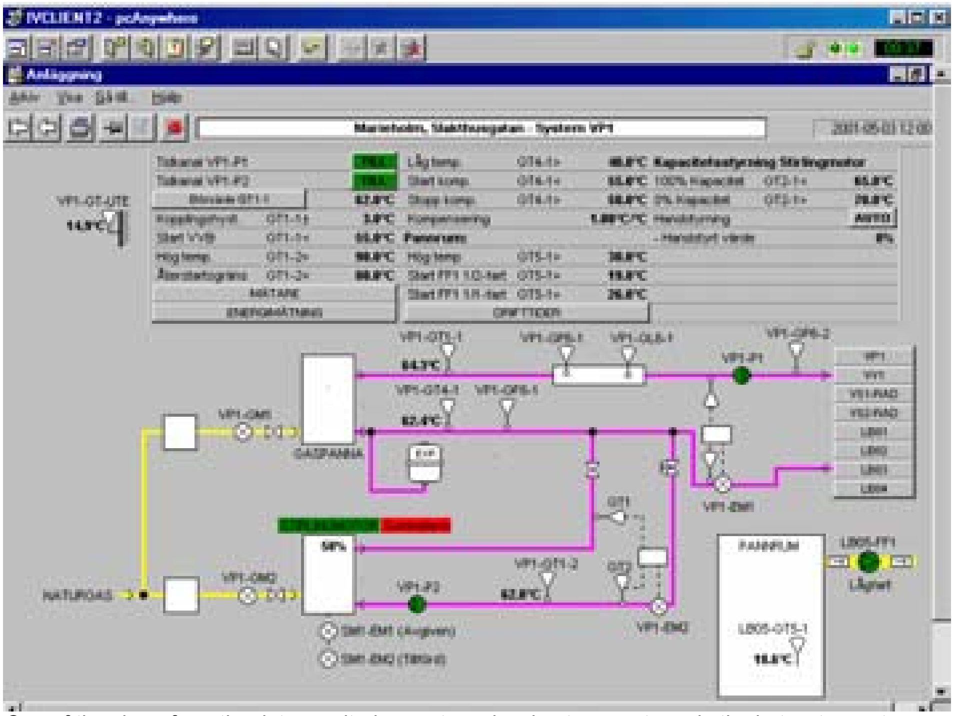


The electrical installation was fairly "straight-forward" since most of the equipment already was included in the Stirling CHP-unit. Two energy meters had to be installed, one for the el. consumption during start-up etc. and the other one for the el. energy that was delivered to the local grid.

The CHP unit was connected to the gas supply system via a new gas meter and the installation was simplified by using the existing supply system to the gas-fired boiler.

The Stirling CHP-unit has it's own built-in control system, but it was also necessary to have an interface with the existing control system, both for control of the total system, remote start of the CHP-unit and for data monitoring. The external system was designed and installed by INU electronic company. The interface between the CHP-unit and the existing system had to be adjusted a number of times during the test period, but a fully satisfying solution was not found during the scope of the project.

In order to evaluate the performance of the CHP-unit, a number of parameters, such as hot water temperature and – flow, el- and heatproduction, gasconsumption etc., were to be monitored and stored in the central system used by Göteborg Energi. This system, DUC, is used for monitoring and supervision of all production facilities installed in the district heating system in Gothenburg from the central control room at the head office. The system is an on-line system, INU-vision v 2.3A, Honeywell INU Control AB, Sweden. By using a modem connection it also became possible to have an on-line view of the CHP-unit operation from the Lund University, Carl Bro and Intersol offices in Malmö and Halmstad.



One of the views from the data monitoring system showing temperatures in the hot water system (GT1, GT2 etc.), control parameter set points etc.
STIRLINGMOTOR – Stirling CHP-unit
GASPANNA – Gas fired boiler

Apart from the view above, other sub-views could be accessed from the screen above presenting el.- and heat output, gas consumption, accumulated operating hours etc. At a later stage of the test period, some of the "internal" parameters from the Stirling CHP-unit were added into the system.

The DUC-system also includes a data acquisition system where the logged data is stored. This system was to be used for data storage in order to make the evaluation of the site tests. The data is stored at five minutes interval, which was sufficient for the long-term evaluation of the CHP-unit. Presentation could be made as graphs or as tables, which could be imported into excel-sheets for further processing. Due to some administrative changes within the Göteborg Energi organization, the data acquisition system for the CHP-unit wasn't taken into operation until September 2001. Some of the data on the unit performance before that date could be estimated thanks to the notes of L. Lundström from Intersol. Unfortunately, the data acquisition system wasn't fully reliable in all respects, which required additional work during the evaluation of the CHP-unit performance.

The mode of operation for the CHP-unit was to be a "manual set point" of 120 bar, i.e. 100 % load, during the winter season, and the "load-control" being the hot water temperature, which gradually reduced the engine load at temperatures above

65 ^{o}C and shut-down at 80 ^{o}C. At a later stage a more integrated system between the Stirling- and the main control system was implemented, but the interaction between the CHP-unit and the outer system with the gas-fired boiler never got quite satisfying. One example being the load-control signal from the main control system causing large load variations on the CHP-unit.

The unit was installed in December 2000 and the first start was made on the 13th of December when the unit was operated for a couple of hours. However, it was almost two months further delay until the unit could be started again. The delay was due the fact that the official approval of the CHP-unit and the gas installation, which was to be made by Göteborg Energi, required a large amount of paperwork, even if the CHP-unit was designed and built with EU certified components. L. Lundström from Intersol carried out the paper work. Finally all papers and certificates were at hand so the final approval could be issued, without any changes in the original installation, and the site test could be started.

4.3 Operational statistics

The first start was made 2000-12-13, but the actual site testing couldn't be started until 2001-02-11. The site test continued until 2002-05-08, but a final set of performance and emission measurements were made 2002-07-03. The unit was returned from Gothenburg to Lund University in November 2002.

The actual site testing period had a duration of 506 days (2001-02-11--2002-05-08). During this time, the CHP-unit had a total operating time of 2100 h, giving a total "availability" of approximately 20 %. This is of course much less than anticipated and doesn't reflect the actual performance of the Stirling CHP-unit. The short operating time mainly originates from two main sources, one being of an administrative nature, the second being disturbances from the external control system and the gas-fired boiler.

The operation of the CHP-unit was hampered by organizational changes that were made within the Göteborg Energi. Originally, one engineer had been appointed for attending the unit, having the main responsibility for the operation and daily supervision etc., but due to the organizational changes this couldn't be fully realized. This had a substantial affect on the operational time of the CHP-unit, mostly due to very long delay before the CHP-unit was restarted after a shutdown.

A number of shutdowns were caused by interference between the internal control system of the CHP-unit and the external control system of the hot water circuit and the gas-fired boiler. This caused numerous stops of the CHP-unit, mostly due to "external factors". However, the situation was improved during the testing period by reprogramming of the external control system. Together with the long "restarting periods" this seriously affected the total operating time of the unit.

During the first test period, from 2001-02-11 until 2001-08-31, data on operating time, el. production and gas consumption have been taken from the manual notes made by L. Lundström, Intersol, when he visited the site for service and maintenance of the unit. The readings were taken from the local meters on the unit. It was not possible to record the hot water production during this time due to incomplete installation of the hot-water metering equipment. Since the readings have been taken at irregular intervals, the data are only presented as a summary of this part of the test period.

During the first test period, the CHP-unit had accumulated approximately 1450 operating hours. During this time the unit had an el. production of about 7200 kWh_{EL} and a gas consumption of about 27500 kWh_{NG}, giving an average el. output of 5 kW_{EL} and an el. efficiency of 26 %.

The data acquisition system was taken into operation 2001-09-01 and data was logged until the testing period was concluded. Unfortunately, the data acquisition system proved to be unreliable in some respects, which didn't become obvious until a detailed evaluation of the logged data was made. The reasons being that some "unrealistic" performance data were found when comparing gas consumption and heat production etc. One example that was found was that the system "on a regular basis" logged about 15 h "extra" operational time after each shut-down. Sometimes the system also logged hot water production even if the CHP-unit was out of operation.

When the erratic data had been eliminated, the second operating period from 2001-09-01--2002-05-07, gave a total operating time of 640 hours, with monthly recordings according to the table below. It should be noted that the output and efficiency data have been calculated as average monthly figures:

		Monthly operational data								
		2001				2002				
		Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Operating time	(h)	32	147	19	7	0	0	239	191	6
El. output	(kW)	2,5	2,5	2,2	3,7			2,9	2,9	5,0
Heat output	(kW)	11,8	n.a.	10,0	16,6			7,9	7,4	15,0
Fuel consumption	(kW)	20,4	19,9	22,0	23,4			13,9	13,6	23,0
El. efficiency	(%)	12	13	10	16			21	21	22
Heat efficiency	(%)	58	n.a.	45	71			56	55	65
Total efficiency	(%)	70	n.a.	55	86			77	76	87
"Alpha-value"	(-)	0,21	n.a.	0,22	0,22			0,36	0,39	0,33
"Availability"	(%)	4	20	3	1			32	27	1

n.a. Data not available due to malfunction in the data acquisition system
The CHP-unit was out of operation in January and February due to inspection of the combustor and general overhaul.

The el. efficiency 2001 is considerably lower than 2002. This reflects that the piston rings were leaking and were replaced during the overhaul in January, see 4.5. The heat meter was malfunctioning during October, giving a constant output of 12,1 kW even when the unit was out of operation.

Some operational periods have been rather short, normally 5-10 hours, which to some extent adds extra inaccuracy to the total figures, for instance due to low efficiency figures during the start up procedure. If only the data covering longer periods of continuous operation, i.e. > 24 h, are used, the Stirling CHP-unit has performed as below:

Operating time (h):	430
Average el. output (kW):	3,1
Average hot water production (kW):	7,7
Average fuel consumption (kW):	13,8
El. efficiency (%):	22,1
Heat efficiency (%):	55,6
Total efficiency (%):	77,7
α-value (-):	0,40

The longest period of continuous operation that has been recorded by the data acquisition system is 214 h (9 days), in March 2003.

It should be noted that all above figures are average data as calculated from the data acquisition system. Generally the unit has been operating at part load, normally about 50 %. One reason for the part load operation has been unsuitable control parameters in the Göteborg Energi main control system which didn't allow full load operation, but in stead started the gas fired boiler. The heat demand during the spring and summer periods were also lower than anticipated. This was boosted by the fact that a new hot water accumulator with a significantly smaller volume than the original one, made it more difficult to get steady operating conditions for the CHP-unit.

4.4 Performance and emission measurements

4.4.1 Measurement methods

Measurements of emission levels and performance on site were made at three occasions, 2001-10-16, 2002-05-07 and 2002-07-03. On the first two dates, the measurements were carried out by personnel from Lund University, Intersol and Carl Bro Energikonsult, while the third set of measurements were carried out by the two first parties, using emission measurement equipment from Carl Bro. Noise emissions were measured 2002-05-07 with a Bruel & Kjaer instrument.

The measurements were made at three load levels; 50, 75 and 100 % load and each set of measurement at steady load conditions were normally carried out during one hour. During each test a number of consecutive readings were taken from the field equipment and manually registered while the emission measurements, NO, NO_2, CO, O_2 and HC, were made and registered with the equipment and methods described below. Personnel from Carl Bro Energikonsult carried out the measurements. Carl Bro Energikonsult is accredited by SWEDAC, Swedish Board for Accreditation and Conformity Assessment, for flue gas measurements of NO, NO_2, CO, CO_2, N_2O, SO_2, O_2 and flue gas flow according to EN 17025. It should be noted that the equipment described below isn't covered by the accreditation, but the measurement accuracy is quite sufficient for this type of field-testing and it was decided by the project working group to use this equipment in Gothenburg.

Measuring methods; NO, NO_2, CO, O_2

The gas components NO, NO_2, CO and O_2 are measured by an instrument Ecom Jn. The principal used in this instrument is electrochemical cells, where a gas component diffuses through a semi permeable membrane to an electrolyte where an electrochemical oxidation or reduction occurs. The electrochemical reaction gives rise to a change in current, which is directly proportional to the content of the gas component. The flue gas is drawn from the flue to the instrument through a heated tube and via a heated filter. The measuring inaccuracy is < 5 % of the measured value.

The instrument is calibrated directly before and after each measurement. Air is used for zero calibration.

Calibration gases:	NO	169 ppm ± 2 %
	NO_2	14 ppm
	CO	456 ppm ± 2 %

Measuring method; HC

The hydrocarbon content in the flue gas is measured with a flame ionization detector, Bernath Atomic 3005. The flue gas is sucked from the flue to the instrument through a heated tube. The lowest measuring interval of the instrument is 0-10 ppm. The measuring inaccuracy is < 4 % of the measured value.

The instrument is calibrated directly before and after each measurement. Air is used for zero calibration.

Calibration gas:	C_3H_8	800 ppm ± 1 %

Data collection

The gas contents are logged continuously in a computer for NO, NO_2, CO and O_2, while the HC-data is collected with a Mitec data logger. The log interval was one minute. All data are measured as % or ppm_{Vol} dry gas.

4.4.2 Measurements 2001-10-16

These measurements were intended to be carried out with a Stirling cycle pressure of 6, 9 and 12 MPa. During the measurements it was found that there was a discrepancy between the cycle pressure and the el. output, with the el. output being lower than expected. This was later found out to be due to wear on the piston rings, which in turn had been caused by an earlier over-heating in the hot water-system. The performance figures originating from these measurements are slightly misleading, but the emission data shows that the emission levels on site are close to those measured in the Lund laboratory.

The measured and calculated data from this test are found in the table below with the emission data measured in the Lund laboratory at a cycle pressure of 12,0 MPa.

It should be noted that the laboratory measurements were focused on the emission data, while the performance data wasn't measured. The cycle pressure represented the engine load and the heat recovered from the unit was cooled off into the laboratory low temperature cooling water system.

Test date			2001-10-16			Laboratory
Stirling pressure	p-St	(MPa)	11,8	9,0	6,0	12,0
El. output	P-El.	(kW)	4,4	3,4	2,2	
Hot water output	P-H.	(kW)	19,0	14,6	9,8	
N.G. Fuel input	P-NG	(kW)	28,0	21,0	16,4	
El. efficiency		(%)	15,7	16,2	13,4	
Hot water efficiency		(%)	67,9	69,5	59,8	
Total efficiency		(%)	83,6	85,7	73,2	
Hot water temp. In	t-I	(C)	50	49	46	
Hot water temp. Out	t-O	(C)	62	57	52	
Lambda		(-)	1,51	1,53	1,47	1,4
O2-level	O2	(%)	7,1	7,3	6,7	6,0
HC-emissions	HC	(ppm)	0	0	0	2
NO-emissions	NO	(ppm)	16	20	48	
NO2-emissions	NO2	(ppm)	3	5	11	
NOx-emissions	NOx	(ppm)	19	25	59	15
NOx-emissions	NOx	(mg/MJ)	14	19	42	
CO-emissions	CO	(ppm)	188	147	147	350
CO-emissions	CO	(mg/MJ)	86	89	195	
CO2-emissions	CO2	(%)	7,8	7,7	8	
Exhaust gas temperature	t-Exh	(C)	265	238	204	200

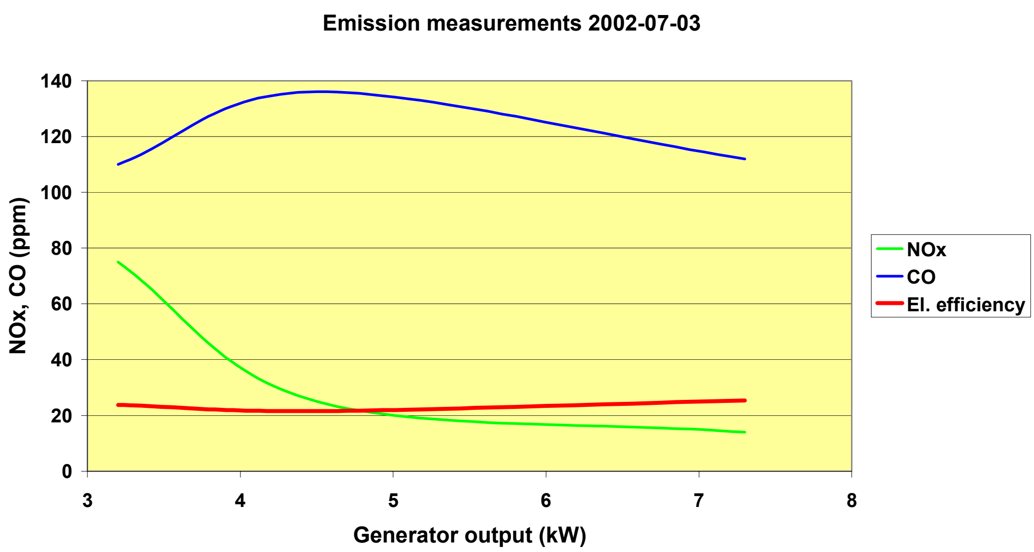
4.4.3 Measurements 2002-05-07 & 2002-07-03

These two sets of measurements showed very similar results and these also confirmed that the emission levels on site were in the same region (with the exception of CO, which was significantly lower on site) as the levels measured in the Lund laboratory.

The performance data showed slight variations between the measurements, but this is mostly a reflection of the temperature variations in the hot water system during the tests. The test results are presented in the table below:

Test date			2002-05-07			2002-07-03		
Stirling pressure	p-St	(MPa)	12,1	9,2	6,0	12,0	9,1	6,1
El. output	P-El.	(kW)	6,8	5,0	3,2	7,3	4,5	3,2
Hot water output	P-H.	(kW)	15,4	11,6	7,2	15,1	11,1	7,4
N.G. Fuel input	P-NG	(kW)	30,5	19,8	12,9	28,8	20,9	13,5
El. efficiency		(%)	22,3	25,3	25,2	25,4	21,5	23,8
Hot water efficiency		(%)	50,5	58,6	56,1	52,4	52,8	51,7
Total efficiency		(%)	72,8	83,9	81,4	77,8	74,3	75,6
Hot water temp. In	t-I	(C)	60	61	62	54	62	60
Hot water temp. Out	t-O	(C)	69	68	66	62	68	64
Lambda		(-)	1,48	1,48	1,47	1,61	1,50	1,49
O2-level	O2	(%)	7,3	7,2	7,2	8,0	7,0	6,9
HC-emissions	HC	(ppm)	1	1	2	0	0	1
NO-emissions	NO	(ppm)	13	17	60	12	22	68
NO2-emissions	NO2	(ppm)	4	6	15	2	3	7
NOx-emissions	NOx	(ppm)	17	23	75	14	25	75
NOx-emissions	NOx	(mg/MJ)	13	17	56			
CO-emissions	CO	(ppm)	156	136	131	112	136	110
CO-emissions	CO	(mg/MJ)	71	62	59			
CO2-emissions	CO2	(%)	8,0	8,0	8,1	7,5	8,0	8,1
Exhaust gas temperature	t-Exh	(C)	249	223	194	239	242	213

NO_x- and CO-emissions and the el. efficiency as a function of the generator load are presented in the graph below and show that these are at a relatively constant level in the normal range of operation for the Stirling CHP-unit, even if the NO_x-emissions start to increase when the load falls below 60 %.



The noise levels were measured 2002-05-07 at a distance of 1 m from the unit. A measurement was also made outside of the building and the noise level was found to be 70 dB(A), but the same levels were measured when the unit was stopped and the noise level measured represents the background level at the site.

Generator load (kW):	3,2	5,0	6,8
Noise level (dB(A)):	77	79	83,5

The noise level at 6,8 kW increased to 92 dB(A) when the hood was removed from the unit.

The conclusions from the measurements are:

- The performance data is comparable to the "standard" Stirling V161 unit.
- The very low emission levels that were achieved in the laboratory tests could be confirmed during the site tests.
- The noise levels 1 m from the unit are relatively modest and the noise level outside the building was below the detection level.

4.5 Maintenance and reliability on site

4.5.1 Estimated maintenance requirements and – costs

Since the operational time during the site test period became very limited as compared to the original plans, it hasn't been possible to make any evaluation of the "typical" reliability or of what could be considered as "normal" maintenance costs. SOLO Kleinmotoren have given the following figures regarding maintenance intervals and – costs:

Normal maintenance intervals are 5000-8000 h. Every second service some burner parts, regenerator, oil and filters have to be replaced. The total accumulated operating time for all of the SOLO Stirling engines is about 180000 h, with one unit still in operation having accumulated 28000 h.

The total maintenance costs, including all spare parts, is estimated to 0,015 EUR/kWh_{EL} (140 SEK/MWh_{EL}), which gives an annual average maintenance cost of approximately 6000 SEK. These figures don't include any cost for personnel.

4.5.2 Experiences from the site tests

As described earlier, most of the malfunctions that were experienced during the site tests, originated from what can be described as "first-installation" specifics and are not typical to the Stirling technology as such. Most of these troubles would have been avoided if more attention could have been paid to the tuning in and adoption of the control interface between the Stirling unit and the external control system, once the initial problems were detected. Some initial "Stirling-problems" were also experienced, primarily concerning the spark plug, which had to be replaced a number of times due to overheating. Some adjustments also had to be made to the control system software, which caused a number of shut-downs without any actual fault being detected. The "Stirling-experiences" are described in more detail in enclosure 2.

The experiences from the site tests are briefly described below. The service and maintenance work has been done by Intersol and partly by Lund University.

Initially a number of overheating problems occurred in the hot-water system. This resulted in deterioration of other components in the Stirling engine. The reason for the overheating problems was malfunction of the external hot-water circulation pump. As a result of the overheating, the internal cooling water expansion tank had to be replaced on two occasions. This was done during the first 500 h of operation. A number of adjustments of transmitters, control system etc. was also performed by Intersol during this period.

After 600 h of operation some cooling water leaks in the Stirling engine were detected and parts of the engine was dismantled. The examination showed that the overheating had damaged the o-ring sealings and consequently all o-rings had to be replaced.

A major examination of the Stirling CHP-unit was made in January 2002 after approx. 1500 h of operation and this revealed some damages, i.e. leaking piston rings which were a consequence of the earlier overheating problems and a structural failure in the flame-holder assembly. The piston rings were exchanged and a modified flame-holder assembly was designed and installed in the unit. The regenerator was also replaced due to the overheating. Otherwise the unit was in very good condition and it could be taken into operation again in the middle of March 2002, when the site test was resumed.

During the site tests, the spark plug had to be replaced a number of times, but the situation improved by using a more heat-resistant type. A number of stops were also initiated by the internal control system indicating high combustion temperatures, but any actual faults could never be detected.

Generally, the unit performed well, and the malfunctions and maintenance work mostly related to “external” problems related to the interface between the Stirling internal control system and the Göteborg Energi external control system. However, the operational time on site was limited, and the unit was mostly operated at a rather low load level, which has reduced the possibilities to make any general conclusions covering “typical” operating conditions.

5 Feasibility study

5.1 Market prospects for micro CHP

There is a strong interest in distributed generation and CHP in many parts of the world. In the United States one important motive for distributed generation of electricity is grid stability and avoidance of grid enhancement. Also the benefits of CHP is recognised by e.g. Department of Energy. In [2] the market for CHP units < 200 kW_{EL} is estimated to more than 45000 units within the next 20 years.

Also in Europe there is an increasing interest in distributed generation and combined heat and power production. Present and future deregulation of the electricity market, however, has introduced some uncertainty regarding the long-term economical competitiveness of distributed generation. [3]

In Sweden, the interest in distributed generation and small-scale CHP has been limited so far. A tradition of centralised production of electricity, low price, a strong national grid and a limited natural gas grid are major reasons for this. Deregulation of the electricity market, together with continued increase in electricity consumption and expansion of the natural gas grid, however, could possibly change the picture. For this to happen, issues like standards and commercial agreements for grid connection have to be solved.

Possible applications for the engine size studied here are among others:

- Office buildings
- Public baths and sport centres
- Small industries
- Residential buildings

It is worth mentioning that the market for micro CHP in Sweden is also limited by the large amount of district heating.

5.2 Investment cost

The investment cost for the V161 Stirling engine CHP-unit – is equivalent to 230000 SEK[2] according to the manufacturer, SOLO Kleinmotoren. In addition to this, the installation cost such as connection to the electric grid, the hot water- and natural gas systems, exhaust gas pipe etc., is roughly estimated to 40000 SEK. [5]

The V161 Stirling engine CHP-unit is available on the market today at the price stated above. SOLO Kleinmotoren have estimated that the price could be reduced by approximately 20 %, if an annual production of 1000 units could be achieved, giving a total investment of 220000 SEK.

[2] 9,20 SEK = 1 EUR

5.3 Fuel cost

The natural gas cost used here is 480 SEK/MWh, including taxes[3] [3] but excluding VAT. This is based on information from the Swedish gas company Sydkraft in September 2003.

5.4 Maintenance cost

The manufacturer states a total maintenance cost including all spare parts etc. of 140 SEK/MWh$_{EL}$.

5.5 Plant economy

In order to judge the plant economy, the cost of electricity is calculated using the annuity method. A depreciation time of 10 years is used and the interest rate is 6 %.

Furthermore, it is assumed that the annual time of operation corresponds to 6000 hours at full load. This depends strongly on the size and variation of the heat load in the system and may differ between applications.

Since not only electricity, but also heat is produced, the delivered heat must be assigned a value. Here, this is based on the cost of heat produced in a gas-fired boiler with 90 % efficiency, approximately 540 SEK/MWh including taxes [3] but excluding VAT. It is assumed that the Stirling engine unit is supplemented by a gas fired boiler for peak load and as stand-by unit of the same size as in the base case without el. production. Consequently, only the operating costs for the gas-fired boiler have been considered in the comparison below.

It is now possible to calculate the cost of electricity (COE) from the Stirling engine using the following input[4].

Electrical output (kW)	7,0
Heat output (kW)	20,4
Fuel input (kW)	30,1
Annual operating hours (h)	6000
Annual electricity production (MWh)	42
Annual heat production (MWh)	122,4
Annual fuel consumption (MWh)	180,7
Fuel cost (SEK/MWh$_f$)	480
O&M cost (SEK/MWh$_{EL}$)	140
Investment cost (SEK)	270 000
Depreciation time (years)	10
Interest rate (%)	6

[3] CO_2 tax 1628 SEK/1000 m^3, energy tax 233 SEK/1000 m^3.
[4] Engine performance based on test results from 2001-09-24 provided by SOLO.

The final calculation is presented as annual costs below.

Cost of capital (SEK)	36 700
Fuel cost (SEK)	86 700
O&M cost (SEK)	5 900
Total cost (SEK)	129 300
Heat income (SEK)	66 100
Cost of electricity (SEK)	**63 200**

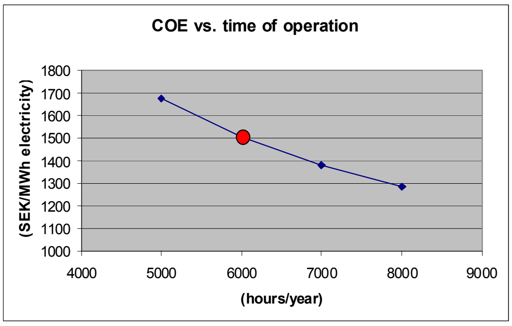
This corresponds to a cost of electricity of 1500 SEK/MWh$_{EL}$ (164 EUR/MWh$_{EL}$). The cost for purchasing electricity from the grid is approximately 50 % of the above, i.e. 770 SEK/MWh[5] including tax and distribution fee but excluding VAT. The Stirling-CHP unit will give an annual loss of approx. 31000 SEK as compared to purchase of electricity and heat production in a gas-fired boiler with the input parameters described above. Hence, it is not economically interesting to produce electricity using this Stirling engine under the conditions stated above.

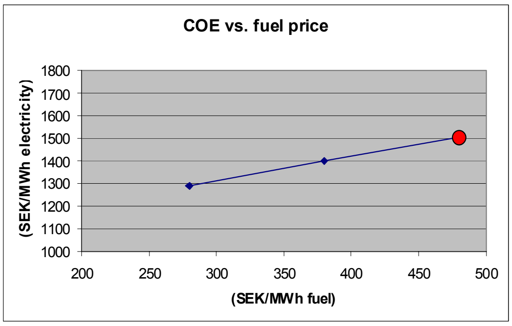
In order to investigate if more "advantageous" (and perhaps more typical for the conditions in other European countries) inputs could change this conclusion, a number of parameters have been varied and the result is presented in the graphs below. Please note that only one parameter has been changed at a time, with all other input equal to what was used above. The base case is marked with a red dot in each graph.

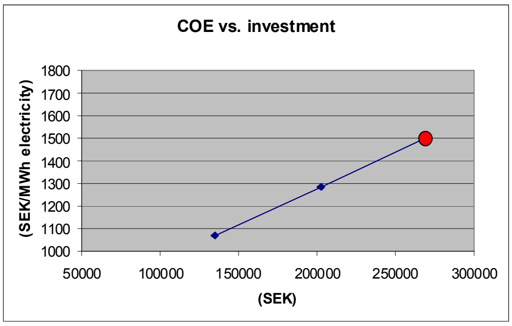
The following parameters have been adjusted:

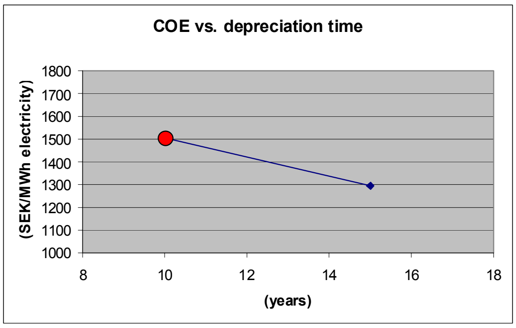
- Annual operating hours 5000-8000 h (- 17 %-+ 33 %)
- Fuel price decreased down to 280 SEK/MWh (- 42 %)
- Investment and installation cost reduced down to 135 000 SEK (- 50 %)
- Depreciation time increased to 15 years (+ 50 %)

[5] Based on fixed electricity price (3 years) offered by Sydkraft in September 2003.









The results shows that the lowest electricity production cost still is above 1000 SEK/MWh$_{EL}$, even if the investment cost is reduced by 50 %, which is well above the present purchasing cost of 770 SEK/MWh$_{EL}$.

The manufacturers estimate with a "mass-production" investment cost reduction of 20 % would give an el. production cost of about 1400 SEK/MWh$_{EL}$, which would give an annual loss of 26500 SEK.

Some combinations of the "best cases" above have also been calculated and the results are presented in the table below.

Combination	**El. Produc-tion cost (SEK/MWh$_{EL}$)**	**Annual profit/loss (SEK)**
Gas fuel cost 280 SEK/MWh + 8000 h annual operation	**1 070**	**16 900**
Investment 135 000 SEK + 8000 h annual operation	**960**	**10 500**
Investment 135 000 SEK + gas fuel cost 280 SEK/MWh	**850**	**3 500**
Reference case (boiler + purchase of electricity)	*770*	--------
Investment 135 000 SEK, gas fuel cost 280 SEK/MWh, 8000 h annual operation	**745**	**1 400**
Investment 135 000 SEK, gas fuel cost 280 SEK/MWh, 8000 h annual operation, 15 year depreciation time	**670**	**5 800**

The conclusions that can be made from the calculations are that there is no obvious market for the natural gas fired Stirling engine CHP-unit in Sweden today. Even the considerable reduction of the present investment cost by 50 % combined with a reduction of the gas price by 200 SEK/MWh gives an annual loss of about 3 kSEK.

In order to get a profitable investment, both the investment cost and the gas price has to be reduced considerably, in the region of 50 % each and the annual operating time has to be increased to 8 000 h. The gas price might be considerably reduced when the market is deregulated, but it is doubtful if the reduction will be as high as 200 SEK/MWh considering that the total tax level today is approx. 180 SEK/MWh. However, this case might represent a "hypothetic"(?) adjustment in the tax system at a deregulated market that supports micro-CHP units with advantageous emission characteristics. A reduction of the investment cost by 50 % seems to be even more hypothetic, since the manufacturer estimate of a realistic investment cost reduction is 20 %.

Alternatively, the electricity price has to increase to a level well above 1000 SEK/MWh$_{EL}$, i.e. by more than 30-50 % without a corresponding increase of the gas price, if the investment in Stirling-CHP shall give more than a marginal profit.

It should also be noted that no economical credits for the advantageous emission levels that have been demonstrated in this project have been taken into consideration in the economical calculations above. This is of course due to the fact that no such credits, such as government financial support for investment costs, tax reductions etc., for "ultra-low emission" CHP-units exist today. If this will be the case in the future, the prospects for the Stirling technology in Sweden might be more prosperous.

Even if the market prospects for the natural gas fired Stirling-CHP technology in Sweden seems rather disappointing, the benefits of the external combustion of the Stirling engine technology could be used for other fuels, where other technologies have some disadvantages, or even can't be considered at all. Such fuels that could be considered are for instance LPG or digester gas, which of course increases the installation area far beyond what presently is covered by the natural gas grid. Other examples are the use of bio-mass combustion or gasification as heat sources for the Stirling engine cycle. Development work is going on in this field and the combination of the CO_2-neutral fuels and the advantages of the Stirling technology can be expected to improve the market prospects in Sweden considerably.

5.6 Comparison with other technologies using natural gas fuel

In addition to Stirling engines, technologies for distributed, small-scale generation of electricity and heat include internal combustion engines, micro turbines and fuel cells. The size studied here (20 kW heat) rules out the micro turbines, since these have a min. size of about 100 kW$_{EL}$, but the fuel cell and the internal combustion engine are possible competitors.

For comparison, data on performance and economy for these technologies are summarised in the table below. The basis for the comparison is that the heat output and heat production are equal for all technologies.

The cost data is derived from [3,4,5,6] and the cost of electricity is calculated according to the base case assumptions in section 5.5. Data for the competing technologies have been scaled to give equal heat output.

	Stirling[8]	**Fuel cell**[9]	**Internal combustion**[10]
Heat output	20 kW	20 kW	20 kW
Electrical output	6,9 kW	15,6 kW	8,3 kW
Electrical efficiency	23 %	35 %	25 %
Fuel utilisation	91 %	80 %	86 %
Investment	270 000 SEK	390 000 SEK	160 000 SEK
Fixed O&M cost	-	11 700 SEK/year	5 900 SEK/year
Variable O&M cost	140 SEK/MWh$_e$[6)]	115 SEK/MWh$_e$[7)]	-
Cost of electricity	**1 500 SEK/MWh**	**1 480 SEK/MWh**	**1 160 SEK/MWh**

The conclusion from this comparison is that the cost of electricity from the Stirling engine is similar to the cost when using a fuel cell and significantly higher than the cost when using an internal combustion engine. It should, however, be noted that the cost data for the fuel cell is based on projections for the “near” future rather than existing installations.

The Stirling engine has some advantages as compared to the conventional internal combustion engine, the main being the considerable lower emission levels as can be seen in the table below.

	Stirling [8)]	**Fuel cell**[9]	**Internal combustion**[10)]
NO_X (mg/MJ$_{Fuel}$)	13	2	83
CO (mg/MJ$_{Fuel}$)	70	26	< 2
HC (mg/MJ$_{Fuel}$)	< 1	---	31
O_2 (%)	7,3	16	7,6

The fuel cell has very low emissions, but these are measured under ideal conditions in a laboratory. Further, the fuel cell technology is the least mature and “commercial” of three technologies above, while the Stirling and the internal combustion engine are comercially available today.

The Stirling unit has much lower levels of NO_x and HC than the internal combustion engine, while the CO level is significantly higher. Since NO_x and some of the chemical compounds that are summarised as HC, are more hazardous than CO, at the levels presented here, the Stirling-CHP unit is especially suitable, and politically acceptable, for installation in domestic environments, while the internal combustion engine could be a more controversial alternative in this respect.

[6] Corresponding to a total O&M cost of 5 900 SEK/year
[7] Corresponding to a total O&M cost of 22 500 SEK/year
[8] Measured in Gothenburg 2002-05-07
[9] [7]
[10] [5]

6 Conclusions

The development of the combustion system at Lund University was successful and the emission targets that had been set up when initiating the project could be achieved. A lot of additional work had to be made on finding suitable control valves and fine-tuning of the control system and control parameters and this caused a delay of this part of the project with almost a year.

The site tests in Gothenburg proved that the emission data from the laboratory tests could be achieved without any problems and that the new combustion system was fully operational in actual site conditions.

The site tests in Gothenburg were not quite successful in the respect that the number of accumulated operating hours was far below the expected. The unit also had to be operated at a relatively low load during most of the time. However, this was not due to any problems with the Stirling CHP-unit, but was a consequence of external factors not actually related to the technology itself. The limited number of operating hours, mostly at part load, makes it difficult to draw any general conclusions regarding the long-time performance of the unit.

One experience was that the installation and approval procedures took much longer than anticipated and delayed the start of the site tests with almost two months.

Another important factor was organizational changes within Göteborg Energi during the project period. This affected the daily supervision of the CHP-unit, which is essential, especially during the first months of operation, when tuning in problems etc. requires extra attention in order to ensure a reliable operation and matching with the hot water system and other production units in the system. The operating conditions and installation of the new unit in the system should also be given more attention. The installation of piping, instrumentation, control system etc. were carried out by different sub-contractors to Göteborg Energi, which made coordination between the different sub-systems more complicated than expected.

Many problems were caused by interference between the existing external control system for the hot water system and gas fired boiler and the internal Stirling control system. Badly scaled control parameters made matters worse for the operation of the CHP-unit and caused numerous “unnecessary” stops of the unit. Initial problems with overheating caused by the hot water system also led to secondary damages on the CHP-unit.

One of the main reasons for the low operating hours was that it sometimes took very long time, sometimes more than a week, before the CHP-unit was taken back in to operation. It also took very long time before the data acquisition system became operational, and it newer became quite reliable. A “local” system would probably have been much more suitable, than the solution of integrating the CHP-unit with the central system used by Göteborg Energi.

When the unit was in operation, it performed very well and emission and performance data were quite satisfying. No problems were experienced with the new type of combustion system, which operated very well, even if a modification had to be done to the assembly. The “external” problems mentioned above could easily be solved in a commercial installation.

The feasibility study shows that the market conditions in Sweden for this type of “micro CHP-units” presently isn’t too prosperous. This is mainly due to a “high” investment cost and the low electricity prices in Sweden, but the situation in other parts of Europe is probably a lot better in this latter respect.

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