Sustainable Energy
Mod.1: Fuel Cells & Distributed Generation Systems

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Lesson XIX: Stirling Engines
Generality of Stirling Engines (1/2)

✓ Alternative machine
✓ Closed cycle
✓ External combustion (high flexibility for fuel)
✓ The general cycle consists of compressing cold gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle
✓ The Stirling engine is noted for its high efficiency (~40%) compared to other small size engines, quiet operation, and the ease with which it can use almost any heat source
✓ The first Stirling engine example was developed in 1816 by Robert Stirling
✓ It is based on a regenerator: an internal heat exchanger and temporary heat store placed between the hot and cold spaces
✓ The working fluid passes through it first in one direction then the other
✓ A typical design is a stack of fine metal wire meshes, with low porosity to reduce dead space, and with the wire axes perpendicular to the gas flow to reduce conduction in that direction and to maximize convective heat transfer
✓ However the recuperator is expensive at not reliable at high temperature
Lesson XIX

Generality of Stirling Engines (2/2)

(a) Isothermal expansion
(b) Constant volume heat-removal
(c) Isothermal compression
(d) Constant volume heat-addition

Recuperator: heat from 2-3 to 4-1
The efficiency of a Stirling ideal cycle is equal to the Carnot cycle efficiency working between the same extreme temperatures ($T_H$ and $T_C$)

So, it works at the highest efficiency value (just the ideal cycle)

Since it is the ideal cycle that is closer to the real cycle, real cycle efficiency is not equal to Carnot efficiency, but is very high (~40% in few kW units)
Stirling Real Cycle

P-V diagram

Pressure (bar \( \text{[bar]} = 0.1 \text{ MPa} \))

90

270

Volume (cc)

1100 1200 1300 1400 1500

A.A. 2011-2012
Stirling Classification

✓ Type α: it is based on two working pistons (as in the generality slide). This configuration has an high specific power, but shows problems for gaskets related to the high temperature cylinder (800°C).

✓ Type β: it is based on one working piston and on a piston displacer used for transferring the gas from the zones (hot and cold) through the recuperator. No high temperature gaskets because the flow insulations are only in the cold cylinder.

✓ Type γ: it is similar to β configuration, but it is more simple for construction because the working piston is located inside a cylinder separated from the cylinder with piston displacer.
Stirling: Type $\alpha$

Type $\alpha$: An alpha Stirling contains two power pistons in separate cylinders, one hot and one cold. The hot cylinder is situated inside the high temperature heat exchanger and the cold cylinder is situated inside the low temperature heat exchanger. This type of engine has a high power-to-volume ratio but has technical problems due to the usually high temperature of the hot piston and the durability of its seals. In practice, this piston usually carries a large insulating head to move the seals away from the hot zone at the expense of some additional dead space.
Stirling: Type β (Type γ Is Similar)

Type β: A beta Stirling has a single power piston arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and does not extract any power from the expanding gas but only serves to shuttle the working gas from the hot heat exchanger to the cold heat exchanger. When the working gas is pushed to the hot end of the cylinder it expands and pushes the power piston. When it is pushed to the cold end of the cylinder it contracts and the momentum of the machine, usually enhanced by a flywheel, pushes the power piston the other way to compress the gas. Unlike the alpha type, the beta type avoids the technical problems of hot moving seals.
Stirling: Other Types

✓ Rotary Stirling engine: it seeks to convert power from the Stirling cycle directly into torque, similar to the rotary combustion engine. No practical engine has yet been built but a number of concepts, models and patents have been produced.

✓ Another alternative is the Fluidyne engine (Fluidyne heat pump), which use hydraulic pistons to implement the Stirling cycle. The work produced by a Fluidyne engine goes into pumping the liquid. In its simplest form, the engine contains a working gas, a liquid and two non-return valves.
Stirling Engines Compared to ICEs (1/2)

Stirling advantages:

- Stirling engine efficiency is higher.
- Stirling engines can run directly on any available heat source (combustion, solar, geothermal, biological, nuclear sources or waste heat).
- A continuous combustion process can be used to supply heat (less emission in comparison with intermittent combustion).
- Most types of Stirling engines have the bearing and seals on the cool side of the engine (they require less lubricant).
- The engine mechanisms are in some ways simpler than other reciprocating engine types (no valves are needed).
- A Stirling engine uses a single-phase working fluid which maintains an internal pressure close to the design pressure (low risk of explosion).
- In some cases, low operating pressure allows the use of light cylinders.
- They can be built to run quietly and without an air supply, for use in submarines or in space applications.
- They start easily and run more efficiently in cold weather.
- They are extremely flexible. They can be used as CHP.
- Waste heat is easily harvested.
Stirling disadvantages:

- Stirling engine designs require expensive heat exchangers.
- The metallurgical requirements are very demanding and costing.
- Dissipation of waste heat is especially complicated because the coolant temperature is kept as low as possible to maximize thermal efficiency.
- Stirling engines, especially those that run on small temperature differentials, are quite large for the amount of power that they produce.
- A Stirling engine cannot start instantly; it literally needs to "warm-up".
- Power output of a Stirling tends to be constant and to adjust it can sometimes require careful design and additional mechanisms.
- The used gas should have a low heat capacity, so that a given amount of transferred heat leads to a large increase in pressure.
- Hydrogen may be the best fluid but it is absorbed by metal and better seals are necessary (safety issues).
- Most technically advanced Stirling engines, like those developed for United States government labs, use helium as the working gas.
- Some engines use air or nitrogen as the working fluid (lower power density, but cheap fluids).
Stirling Engine by STM Power Inc. (1/2)

✓ Electrical power: 55 kW
✓ Generator set for combined heat and power applications.
✓ The total enclosure length is about 2.5 metres, and this assembly has a mass of about 1300 kg.
✓ Based on an external combustion chamber and a heat exchanger.
✓ Number of cylinders: 4
✓ Generator: 55 kW induction motor (used also for start-up).
✓ Working fluid: hydrogen (replenished by an electrolyzer)
✓ Small blower to force combustion air into the burner assembly.
✓ The blue hoses circulate cooling water through the cool-side.
✓ The Stirling is designed for auxiliary power and heat production at large farms, or for plants that produce waste flammable oils.
✓ This engine can also be adapted to run on low-heat-value landfill gas or biofuel digester gas.
Stirling Engine by Genoastirling (1/2)

- Model name: GENOA03
- Electrical power: 3 kW
- Generator set for combined heat and power applications.
- Based on an external combustion chamber and a heat exchanger.
- Number of cylinders: 2

<table>
<thead>
<tr>
<th>Mechanical specifications</th>
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<tbody>
<tr>
<td>Cylinder volume</td>
<td>880 cm³</td>
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<tr>
<td>Number of cylinders</td>
<td>2</td>
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<tr>
<td>Working fluid</td>
<td>Air or helium</td>
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<tr>
<td>Maximum pressure</td>
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<tr>
<td>Start-up temperature (hot side)</td>
<td>520°C (793.15 K)</td>
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<tr>
<td>Nominal temperature (hot side)</td>
<td>750°C (1023.15 K)</td>
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<tr>
<td>Nominal rotational speed</td>
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<tr>
<td>Electrical nominal power</td>
<td>3 kW</td>
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<td>Thermal nominal power</td>
<td>25-30 kW</td>
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<tr>
<td>Lubrication</td>
<td>Not necessary</td>
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<tr>
<td>Maintenance</td>
<td>Inspection every 1000 h</td>
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Stirling Engine by GenoaStirling (2/2)

1. Electrical generator
2. Carter
3. Engine block
4. Cooler
5. Reciprocator
6. Hot side heat exchanger