Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

GEOTHERMAL ELECTRICITY PRODUCTION BY MEANS OF THE LOW TEMPERATURE DIFFERENCE STIRLING ENGINE

Ivo Kolin[1], Sonja Koscak-Kolin[2], Miroslav Golub[3]
[1,2,3]Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia

Key Words: geothermal power generation, Stirling motor, thermodynamic efficiency

ABSTRACT

The first low-temperature difference Stirling engine was presented at the International University Center in Dubrovnik, as early as 1983. During the last 16 years, numerous low temperature difference engines were built all over the world, mostly for solar energy application. However, hot water from flat solar collectors has nearly the same temperature as hot water from geothermal sources. As the engine power depends upon the cube of temperature difference, geothermal wells of elevated temperatures, approaching the boiling point, are particularly suitable for Stirling engines. When compared to the classic Clausius-Rankine cycle, mostly used in the present geothermal plants, Stirling cycle offers many theoretical and practical advantages. From thermodynamic point of view, **Stirling** cycle is equivalent to the optimal **Carnot** cycle, having the highest possible efficiency. From the technical point of view, Stirling plant is cheaper, having no condenser and no turbine blades exposed to aggressive influences of geothermal steam. Due to the external, instead of internal heating, there is no need neither for specific materials, nor for tube exchangers. The latest performance of low temperature difference Stirling engine using hot water, was made by Japanese group at Saitama University, showing additional possibilities for use of geothermal sources.

1. INTRODUCTION

The most outstanding feature of the Stirling engine described here is its ability to work at low temperatures, namely below the temperature of boiling water. More precisely, even the temperature of the human body is sufficient to put the engine into motion. Such a kind of an engine can use low temperature energy sources that are widespread in nature: the hot water from flat solar collectors, geothermal water, and hot industrial wastes.

The first Stirling engine was built by Rev. R. Stirling as early as 1815, when thermodynamic science entered the most significant period of its development. There are ten elementary power cycles which follow from the combinations of five typical thermodynamic changes of state (Fig. 1) :

1. (2 ib + 2 it)	Ericsson	1853
2. (2 ib + 2 pt)	Cayley	1807
3. (2 ib + 2 ad)	Joule	1852
4. (2 ib + 2 ih)	Papin	1690
5. (2 it + 2 pt)	Reitlinger	1873
6. (2 it + 2 ad)	**Carnot**	**1824**
7. (2 it + 2 ih)	**Stirling**	**1815**
8. (2 pt + 2 ad)	Lorenz	1894
9. (2 pt + 2 ih)	Crossley	1896
10. (2 ad + 2 ih)	Otto	1867

2. STIRLING MOTOR PRINCIPLE

The first Stirling engine was also the simplest and may be taken as a school example to illustrate the working principle, which is based on the simultaneous heating and cooling of a long metal cylinder (Fig. 2) :

- The motor consists of two cylinders, with two pistons which are moving under a phase difference ($\Delta\varphi$) of about 90°C.
- The working piston is placed in the smaller working cylinder.
- The long piston in the long cylinder is essentially not a piston, it is called a displacer and works as a heat exchanger.
- Diameter of a long displacer piston is for about 1 % smaller than cylinder diameter. Through this narrow annular space, the displacer piston moves the air from the cold to the hot space and vice versa.

Compression: While the displacer piston is situated in the lower part of the cylinder, the entire quantity of air is in the cold space. At this moment the cold air is compressed by the working piston.

Expansion: While the displacer piston is situated in the upper part of the cylinder, the total quantity of the air is in the hot space. At this moment the expansion of the hot air drives up the working piston.

Work or energy: As the expansion of the hot air gives more work than is spent by compression of cold air the surplus is the useful work on the working shaft.

Due to the influences of the dead space and sinusoidal pistons motion, the actual indicator diagram is rounded and smaller than it should be according to the isothermal cycle.

2.1 Stirling cycle efficiency

Thermodynamic efficiency of Stirling motor is the ratio between useful work (je) and the heat supplied (q_*), as shown together with the Temperature-entropy (T, s) diagram (Fig. 3). Stirling cycle efficiency (η_S) is also equivalent to the optimal Carnot cycle efficiency (η_C), which is calculated as a ratio between temperature difference (ΔT) and maximum temperature (T_{max}).

3. THE FIRST FLAT-PLATE STIRLING ENGINE

Low temperature difference flat plate Stirling engines are made all around the world mostly because they are simple and cheap. The first flat plate engine was presented at Dubrovnik in 1983. The original prototype was fueled by hot water and was working under temperature difference of 20°C (Fig. 4).

During the long research period Prof. Kolin built 16 experimental engines logically connected to each other, aiming to reach the ideal isothermal cycle, as near as possible (Fig. 5).

The essential difference between the classic engine and the flat plate engine is more practical than theoretical. As a contrast to the long standard cylinder, the short power box contains a short displacer plate, enabling a rapid motion. As a consequence of the fast motion, both the isochoric lines are completed, resulting in an ideal instead of a rounded cycle. Such a good approach to Stirling cycle is achieved by means of thermodynamic advantages of the flat plate exchangers and discontinuous motion.

4. GEOTHERMAL POWER GENERATION

Today it is generally presumed that commercial geothermal power-plants work only with high temperature steam, while geothermal water is applicable only for direct use. As a contrast to that, the new development of the Stirling engine showed that the low temperature geothermal sources can also be successfully used for the conversion of heat into the mechanical work and then into electric power.

There are several possibilities to generate geothermal power with respect to the thermodynamic properties of geothermal water (Fig. 6):

4.1 Open cycle

Shorter adiabatic expansion ends by an atmospheric pressure (1 bar) instead of a condensing pressure (0,004 bar). This is the simplest cycle having a small power and efficiency.

4.2 Clausius-Rankine cycle

Steam-water mixture is led to the separator and the separated steam is admitted to the steam turbine. CO_2 is extracted by turbo blowers.

4.3 Combined flash cycle

Secondary steam, separated from the remaining hot water, in the low pressure flasher, is led to the intermediate turbine stage.

4.4 Binary cycle

Due to the lower boiling point of the organic fluid supercritical Clausius-Rankine cycle could be realized even from the brine of moderate temperature.

4.5 Stirling cycle

Binary cycle, using Helium as a working fluid, could work upon a low ΔT Stirling cycle as well. After removing the heat, brine is reinjected, preventing CO_2 pollution.

The low temperature potential of some geothermal reservoirs is their major disadvantage when it comes to power generation, since the above mentioned processes require reheated steam for their operation. Thus, Stirling cycle seems to be a better and more practical solution resulting in considerably higher efficiency, because it is thermodynamically equivalent to the optimum Carnot's cycle. The development of Stirling engine with the flat plate heat exchangers (Stirling-Kolin engine) has shown that the low temperature geothermal reservoirs may also be successfully used for conversion of heat into mechanical work or electric energy.

Hot water from the well circulates through a number of flat boxes connected with a crankshaft driven by a generator. After transferring its heat to the plant, the cooled water is returned into the reservoir using an injection pump. Additionally, the geothermal plant using the Stirling cycle has considerable technical and economic advantages when compared to the classic Clausius-Rankine process because there is no evaporator, condenser, fead water pump and numerous other associated elements.

Table 1 shows how low ΔT engines can reach 1 kW power. According to the simplest equation called the square rule, the first approximation of power can be calculate knowing only the box length in meters (a) : $P = 0,253 * a^2$ (kW).

Flat plate engine with box side length of 2 m could achieve approximately 1 kW power in an ideal case. If these huge plate areas are transformed into smaller ones making any modular variations from the table, power is the same (Table 1).

Another possibility is a new low ΔT Stirling motor having a classic cylinder, which presently is being developed at Saitama University (Fig. 7). According to the latest data it is reaching nearly 0,7 kW power under ΔT of about 80°C. This type of an engine is considered in further power calculations for geothermal field "Mladost" in Zagreb (Croatia).

5. POWER GENERATION AT GEOTHERMAL FIELD MLADOST-ZAGREB

All the thermodynamic processes for the conversion of heat into mechanical work, and in particular for the low temperature resources, are dependent upon the ambient temperature. Each heat engine is working better during the winter than during the summer time, which is very important for the geothermal fields is Croatia. The major part of our fields has a temperature below the boiling point of water so calculations cannot be performed by the yearly average temperature.

Calculation of power should be repeated for each month based on the average temperatures, as shown in Table 2. The outlet temperature from well is **80°C** and geothermal water delivery (D) is 5000 m^3/day = 208333,33 kg/h :

Numerical example for JANUARY :

1.	Total working hours	$z = 31$ days*24 h*β = 774 h*0,8 $z \approx 619$ h
2.	Temperature difference	$\Delta t = 79,4^oC$ (from Table 2)
3.	Heat supplied	$Q = D*c_P*\Delta t$ $Q = 208333,33*1/860*79,4$ $Q = 19234,5\ kW_t$
4.	Carnot efficiency	$\eta_C = \Delta T / T_{max} = 79,4/(80+273)$ $\eta_C = 79,4/353 = 0,2249 \approx 22,5\%$
5.	Power	$P = Q*\eta_C = 19234,5*0,225$ $P = 4326,4\ kW_e$
6.	Electricity production	$E = P*z = 4326,4*619$ $E = 2678041,6$ kWh

6. CONCLUSION

The transformation of geothermal heat into mechanical or electrical work is generally discussed mostly for the relatively large scale of several thousands kW or so. As a contrast to this, the small range of power of a few kW is more neglected in the case of geothermal resources. Nevertheless, only one kW power could be quite sufficient to drive a circulation pump for a very large quantity of geothermal water in very different applications. Practical examples could be space heating, various technological processes using moderate temperatures and other similar systems. All these examples require a great amount of heat, but relatively small pump to move around hot geothermal water. For the time being, low temperature difference Stirling motors, driven by hot water are not available in large power units. However, due to the promising contemporary development of geothermal Stirling engines, ever-growing power units will most likely soon be available to cover increasing energy needs as well.

REFERENCES

Kolin I., (1995). *Thermodynamic theory for Stirling cycle machine design,* 7th International Conference on Stirling Cycle Machines, Waseda University Tokyo, 1995, p. 1-7

Kolin I., (1984). *Low temperature difference Stirling engine*, 19th Intersociety Energy Conversion Engineering Conference, San Francisco, paper No 849 029

Kolin I., (1990). *Stirling motor - history - theory - practice*, Zagreb University Publications, Zagreb, 285pp.

Naso V., (1991). *La Macchina di Stirling*, Editoriale ESA, Milano, 471pp.

Toda et al, (1995). *Development of 300 W class low temperature difference Stirling engine,* 7th International Conference on Stirling Cycle Machines, Waseda University Tokyo, p. 437-443

Golub M. et al, (1997). *GEOEN - geothermal energy usage in Republic of Croatia*, Energy I. "H. Pozar", Zagreb, 99pp.

Koscak, S. and Cubric S. (1998). *Stirling motor driven by geothermal energy,* International Course New and renewable energies and Stirling engine, Dubrovnik, Croatia, p. 62-67

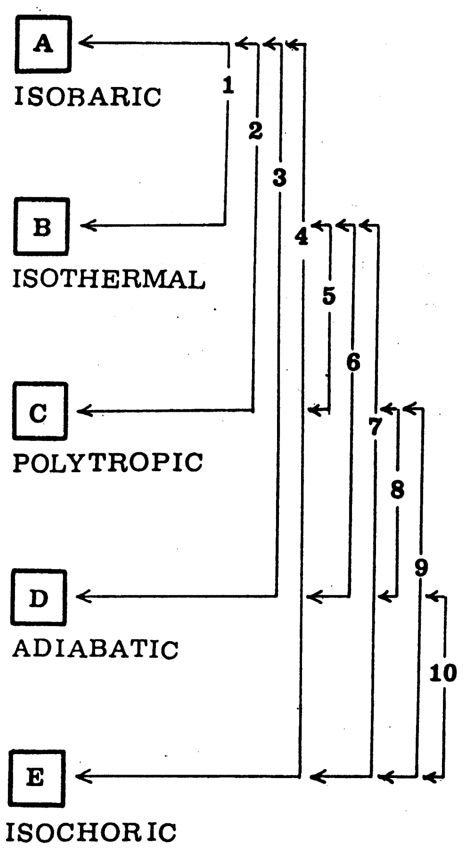


Figure 1. Ten elementary thermodynamic cycles

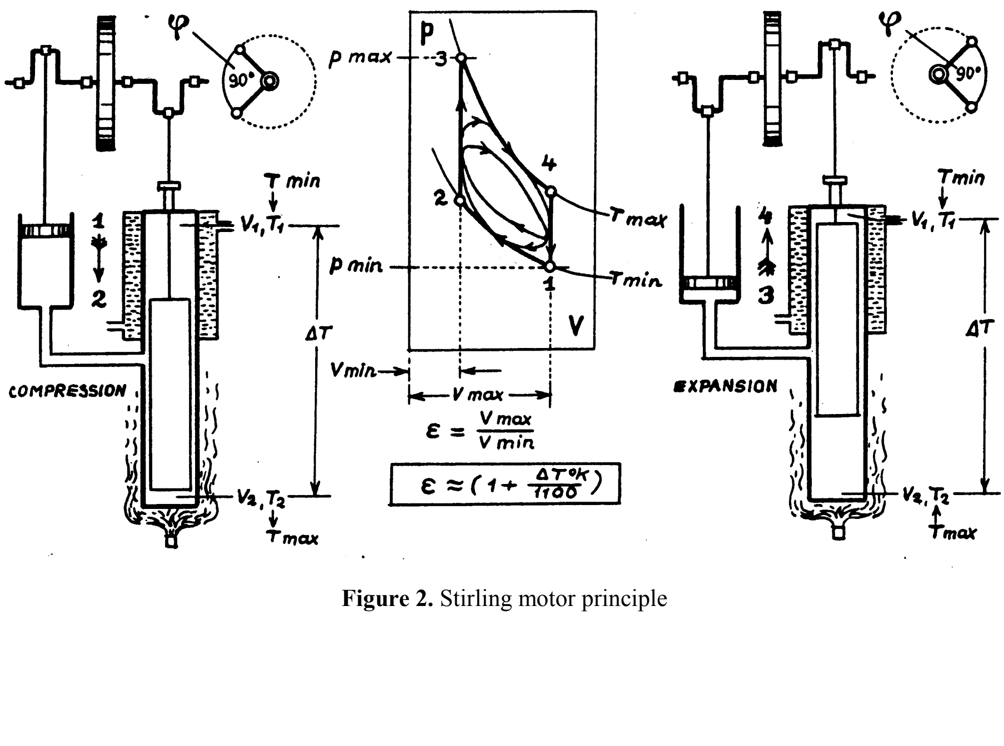


Figure 2. Stirling motor principle

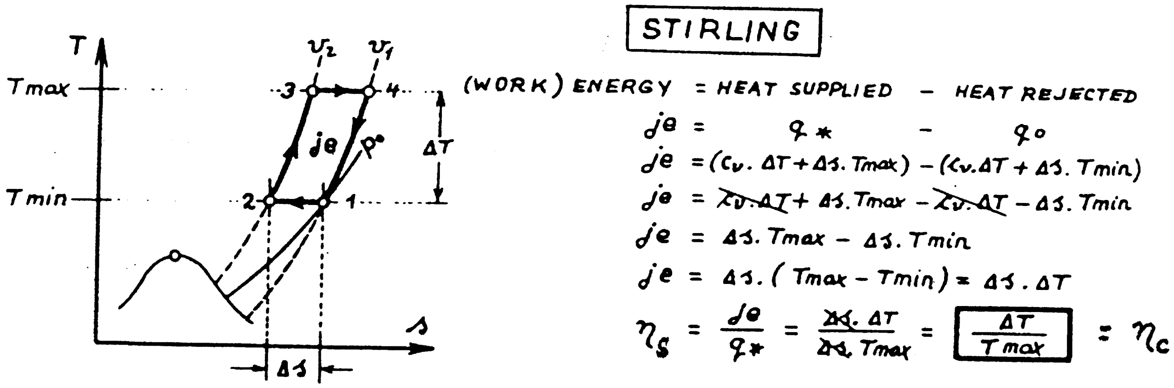


Figure 3. Stirling cycle efficiency

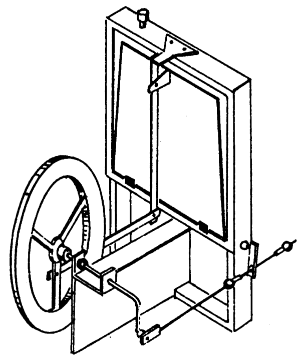


Figure 4. The first flat plat low temperature Stirling engine

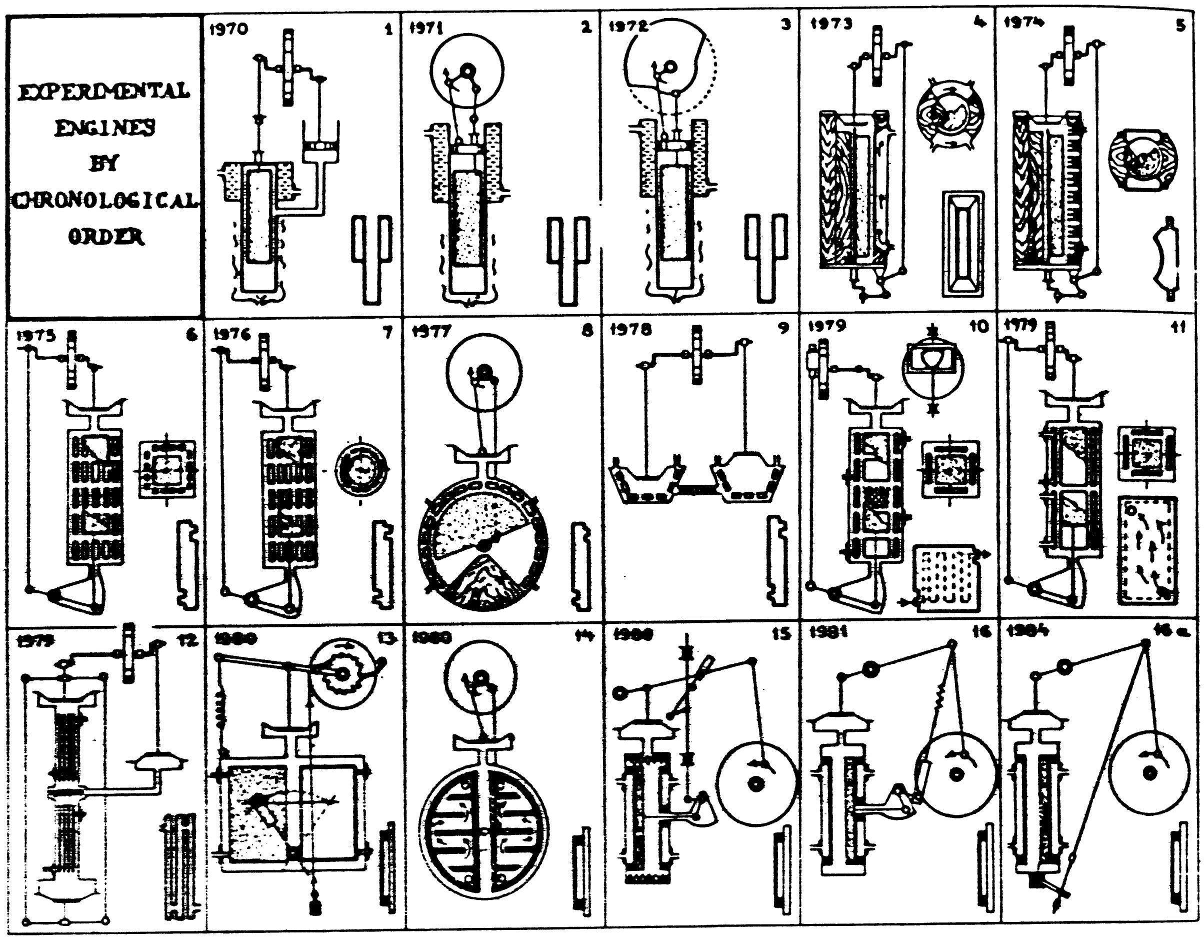


Figure 5. Experimental engines in chronological order

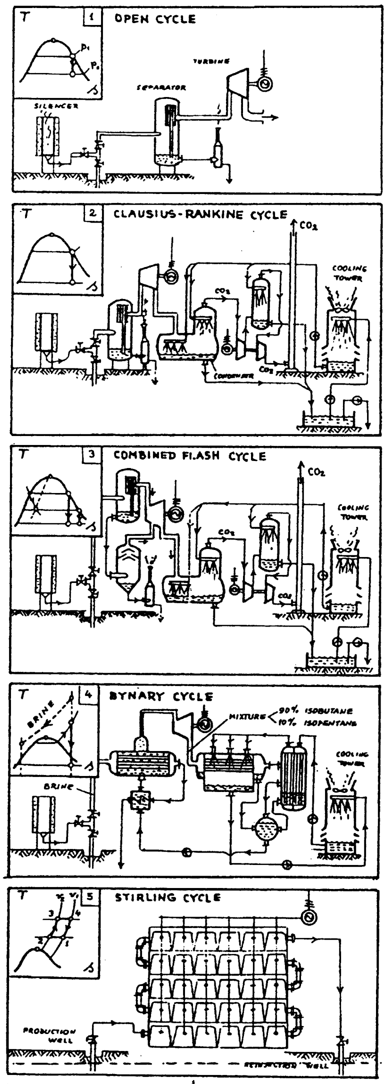
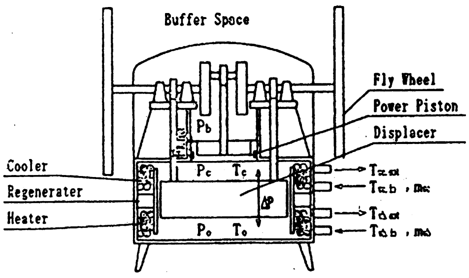


Figure 6. Geothermal power generation



Engine type		γ type
Power piston	Bore	Any value
	Stroke	200 mm
	Swept volume	
Displacer	Bore	2 × Power piston bore
	Stroke	80 mm
	Swept volume	Each volume
Heater	Volume	0.3 × Displacer volume
Cooler	Volume	0.3 × Displacer volume
Regenerator	Volume	0.15 × Displacer volume
	Type	Metal wire matrix
	Number of matrix	35
Compression ratio		1.3125

Figure 7. New Stirling motor fueled by geothermal energy

Table 1. Power calculation for modular construction

BOX LENGTHS	AREA OF 1 PLATE	SQUARE RULE FOR POWER	POWER OF 1 ENGINE	MODULAR ELEMENTS	TOTAL POWER
2 m x 2 m	4 m^2	$P = 0,253 * 2^2 =$	1,012 kW	1	1,012 kW
1 m x 1 m	1 m^2	$P = 0,253 * 1^2 =$	0,253 kW	4	1,012 kW
0,5 m x 0,5 m	0,25 m^2	$P = 0,253 * 0,5^2 =$	0,063 kW	16	1,012 kW
0,2 m x 0,2 m	0,04 m^2	$P = 0,253 * 0,2^2 =$	0,01012 kW	100	1,012 kW

Table 2. Data for the power calculation for the geothermal field “Mladost”

MONTH	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
t_o℃	-0,6	1,9	5,3	9,4	19	21,6	23,7	22,9	18,5	9,7	3,9	1,2
Δt℃	79,4	78,1	74,7	70,6	61,0	58,4	56,3	57,1	61,5	70,3	76,1	78,8
η_C%Carnot	22,5	22,1	21,1	20,0	17,3	16,5	15,9	16,1	17,4	19,9	21,5	22,3