Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Alternative Ways of Utilising Geothermal Energy by Means of a Module Based on the Stirling Engine for Electricity Production

Mirosław Janowski

Ul. Rysi Stok 13; 30-237 Kraków; Poland

janowski@agh.edu.pl

Keywords: geothermal energy, Stirling engine, low enthalpy, electricity generation

ABSTRACT

Geothermal energy in Poland is used exclusively for heating purposes. This takes place in classical geothermal heating plants, as well as in balneology and recreational systems. One may frequently come across postulates to utilise the earth's thermal energy for the production of mechanical energy and further on electricity.

This paper regards thermodynamic and energy conditions of using low temperature geothermal waters for the production of electricity.

A Stirling engine has been used for modelling the conversion of thermal (geothermal) energy into mechanical energy.

The said engine has been selected as an alternative to expensive ORC cycles (Organic Rankine Cycle), which are difficult from the technological point of view. A Stirling engine operates on a gas cycle (without fluid phase change). Heat-transfer fluids can be such noble gases as argon or helium, but also ordinary gases, e.g. carbon dioxide, nitrogen or air. Hydrocarbons may be used as heat-transfer fluids as well.

The former are expensive and it is difficult to acquire device tightness, but they guarantee higher circulation efficiencies. The latter have explosive properties, while air and carbon dioxide are commonly available and they do not pose any risks to the environment or people, although they do not guarantee relatively high efficiency.

The considerations have been performed for relatively low temperatures of the upper source, corresponding to the Polish operating conditions, i.e. ca. +80^{o}C. The lower heat source is presented in the form of a natural heat receiver, i.e. groundwater or air.

The whole solution has been presented in the form of an additional element installed on an operating geothermal plant. It has the form of a heat exchanger generating electricity in especially adjusted Stirling engines.

1.0 ALTERNATIVE WAYS OF UTILISING GEOTHERMAL ENERGY BY MEANS OF A MODULE BASED ON THE STIRLING ENGINE FOR ELECTRICITY PRODUCTION

One may say that geothermal energy is common, so why is it not used so commonly? There is a simple answer to this question.

First of all, it is energy difficult to acquire, we may even say it is inaccessible; secondly, it is scattered and difficult to harness, and thirdly, geothermal plants are expensive at the investment stage. They are not cheap also at the operational stage, despite seemingly free energy carrier.

The utilisation of geothermal energy for heating purposes relates to a relatively low plant loading coefficient, which results in low profitability of such plants. It is especially visible while using the energy of geothermal waters with low enthalpy, which we have to deal with in Poland. The temperatures of geothermal waters below 100^{o}C may guarantee only a possibility of using them for heating purposes. It is advisable to support such plants with a peak-load boiler, which improves the load coefficient (of using the geothermal system and, contrary to general opinions, it contributes to the improvement of ecological parameters of the investment project, through increasing avoided emissions resulting from the operation of a geothermal heating plant).

The best way of disposing of energy from any source is its highly efficient transformation into electricity in a plant operating with a high load (utilisation) coefficient. The best situation is when the plant load coefficient is 1; in such case, the plant operates practically all year round with full power. It is practically impossible, whereas, e.g. a realistic load coefficient of a geothermal heating plant ranges from 20 to 40%.

Electricity production by means of heat coming from geothermal waters is successfully conducted in such countries as Iceland, USA, Italy, etc. The easiest way to do it is to use waters with relatively high enthalpy, allowing operation based on the Rankine cycle, utilising steam as working fluid. One may also use waters with lower enthalpy, based on organic Rankine cycles (ORC) or Kalina cycles, operating on the basis of water and ammonia as heat-transfer fluid.

Both ORC and Kalina cycles used for electricity generation are quite complex and they pose a risk of environmental contamination, or even an explosion hazard.

They do not have high efficiency, either, as it ranges from several to a dozen percent.

A thermal machine permitting generation of mechanical energy and further on electricity, utilising sources of thermal energy with low temperature is a simple Stirling engine. That engine was invented in 1816 by Robert Stirling, a clergyman from Scotland. It is a unit operating in a gas closed cycle, where any gas may be used as heat-transfer fluid.

The author decided to analyse the usefulness of the Stirling engine to the above-mentioned applications. Several (7) engine sizes, with the characteristic feature being cylinder volume, Vc, were taken into consideration. The volumes were the following: 1,000 cm^3, 500 cm^3, 200 cm3, 100 cm^3, 50 cm^3, 20 cm^3 and 5 cm^3. For those values, cylinder diameters, dc, were optimised. They were as follows: 10.838 cm; 8.602 cm; 6.338 cm; 5.030 cm; 3.992 cm 2.942 cm and 1.853 cm. Those sizes determined the piston surface and stroke, stemming also from the assumed engine displacement. Temperatures of the upper heat source equal to 80°C and of the lower heat source equal to 20°C were assumed for the considerations. In the analysis, air under the pressure of 10 bars was assumed as heat-transfer fluid in the cylinder.

Next, efficiencies of the ideal Carnot cycle were calculated, together with the theoretical thermal efficiency. They were η_c= 0.1698 and η_t = 0.0517, respectively. These are not high values, but one cannot say that they were very small, compared to the parameters of the ORC cycles.

The next step was to find a factor determining heat stream supplied to the Stirling engine cylinder, or more exactly, to the fluid stored in it. That value depends on the parameters of the cylinder wall and on the parameters of the fluid heating the warm cylinder and the refrigerant cooling the cold cylinder. In the case under analysis, it was assumed that it is water with the heat transfer coefficient, α= 10,000 W/m^2. The last element stipulating the amount of thermal energy, which may be transferred to heat-transfer fluid, is the coefficient of heat transfer from the cylinder wall to gas in the cylinder and the temperature of that gas. The heat transfer coefficient is directly proportional to the rate of fluid flow in the cylinder, expressed with the dependence (Recknagel, Spreinger and Schramek 2008).

On the other hand, the fluid flow speed in the cylinder, the higher the flow, the smaller the cylinder diameter and the higher the engine rotations (Figure 1). Rotations will be the higher the more energy will be supplied to the cylinder in time unit.

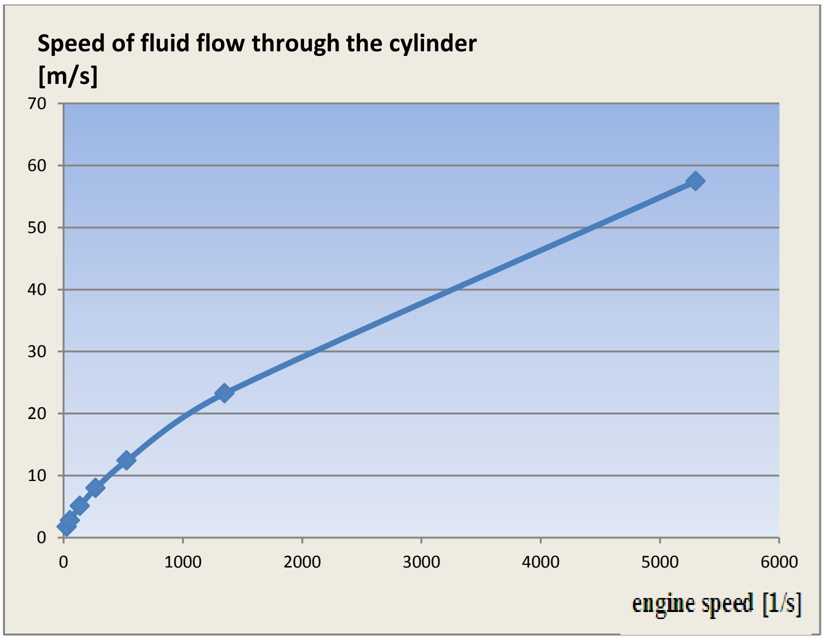

Figure 1: Dependence between the speed of fluid flow in the cylinder and the engine speed

Due to the fact that in this case we cannot obtain direct dependence between the engine size and its power, because of the relation between those two values, being engine rotations unspecified in thermodynamic equations, it was decided to make iterative calculations, by entering the results acquired from the energy and weight balance into the equation determining the parameters of the Stirling engine operation. Finally, the results obtained were very similar, which has been illustrated in Table 1.

Table 1. A table illustrating input data, thermodynamic parameters of engine operation and acquired values of unit heat streams and power acquired for particular Stirling engine sizes.

Description	Unit	Value						
volume of warm cylinder	cm^3	1000	500	200	100	50	20	5
volume of cold cylinder	cm^3	200	100	40	20	10	4	1
diameter of warm cylinder	cm	10.838	8.602	6.338	5.030	3.992	2.942	1.853

diameter of cold cylinder	cm	6.338	5.030	3.706	2.942	2.335	1.720	1.083
surface of warm cylinder	cm^2	92.263	58.122	31.55	19.877	12.522	6.798	2.697
surface of cold cylinder	cm^2	31.553	19.877	10.791	6.798	4.282	2.324	0.922
thermal efficiency		0.0517	0.0517	0.0517	0.0517	0.0517	0.0517	0.0517
Carnot efficiency		0.1698	0.1698	0.1698	0.1698	0.1698	0.1698	0.1698
heat transfer coefficient in warm cylinder	W/m^2K	62.045	94.250	160.409	237.706	351.199	607.818	1345.511
heat transfer coefficient in cold cylinder	W/m^2K	21.242	34.187	62.801	98.598	154.336	288.303	716.365
heat stream taken	W	4.229	4.288	4.276	4.229	4.170	4.229	4.170
heat stream given	W	4.021	4.077	4.066	4.021	3.965	4.021	3.965
power	W	0.207	0.210	0.210	0.207	0.205	0.207	0.205
power from volume unit	W/cm^3	0.000173	0.000351	0.000876	0.001733	0.003417	0.008663	0.034171
power from surface unit	W/cm^2	0.000442	0.000712	0.001308	0.002054	0.003215	0.006005	0.014922
power from surface unit in W/m^2	W/m^2	4.424	7.121	13.081	20.538	32.148	60.053	149.219
flow rate in hot cylinder	m/s	2.926	4.731	8.683	13.583	21.162	39.717	98.228
flow rate in cold cylinder	m/s	1.711	2.766	5.078	7.943	12.375	23.226	57.444
rotations	1/s	27	55	137	270	530	1350	5300
rotational speed calculated based on the weight and energy balance	1/s	26.811	54.365	135.541	268.110	528.755	1340.550	5287.551

The change in the coefficient of heat-transfer to the cylinder for particular cylinder sizes has been presented in Table 1. As can be seen, it increases considerably, together with a decrease in the cylinder size and an increase in engine rotations (Figure 2).

The next stage of the considerations was to determine power acquired from the volume unit of the Stirling engine cylinder. Observations were made, which show that power per 1cm^3 of the cylinder volume decreases together with an increase in cylinder volume. This phenomenon is highly understandable, due to low temperatures, so heat exchange takes place practically only through convection, which in case of large cylinder volume is very difficult (Figure 2).

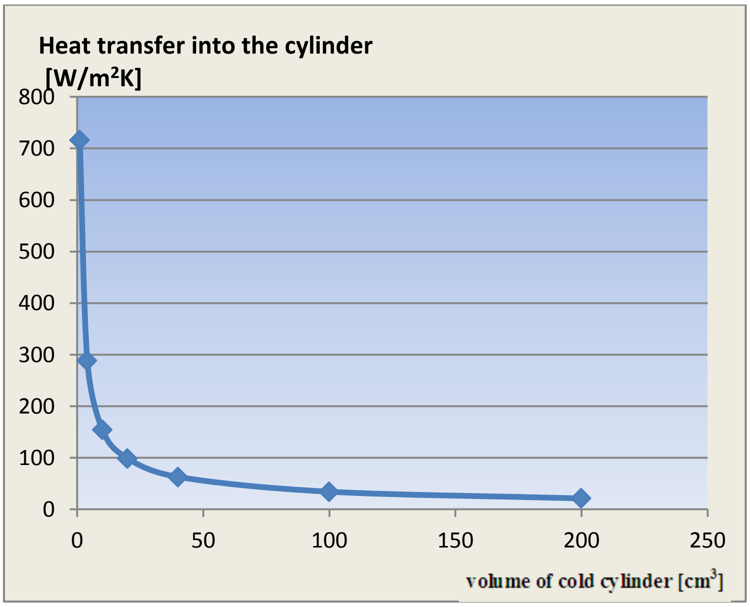

Figure 2: Dependence between the coefficient of heat transfer to and from the cylinder and the cylinder volume.

It is obvious that theoretical considerations can be much different from actual values, but it is undeniable that the smaller a Stirling engine, the higher rotations it reaches and its energy efficiency is higher.

It leads to a simple conclusion that several small Stirling engines will be more energy efficient than one large one with stroke volume corresponding to them. Following this path of reasoning, we can assume for electricity production from geothermal waters with low enthalpy something like a counter-current diaphragm heat exchanger (the electro-energetic Stirling-Janowski module), in which a diaphragm between warm (heating) and cold (cooling the engine) agent is an insulating plate with many small Stirling engines installed as in Figure 3, i.e. a warm cylinder is washed by hot fluid, whereas the cold cylinder by a refrigerant. The insulating plate prevents unproductive heat transfer from warm to cold fluid, omitting Stirling engines, which would result in significant decrease in energy expenditure of a device.

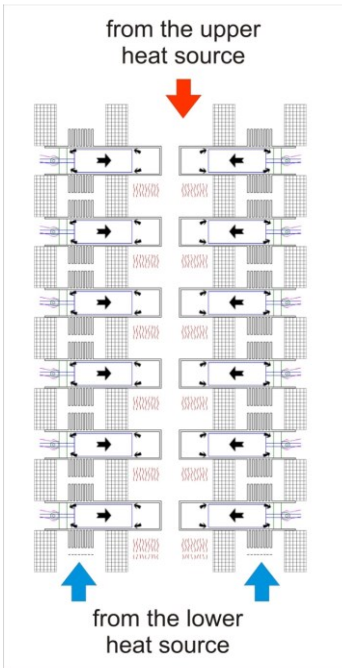

Figure 3: Schematic diagram of the element generating electricity.

The solution of that kind, while guaranteeing appropriately high flow of heating and cooling medium, permits maintenance of practically constant temperature of the lower and upper heat source. Obviously, it cannot be the only utilisation of geothermal waters, since it would mean low efficiency, but if it is implemented as in Figure 4, it may constitute supporting or emergency energy source for the geothermal system

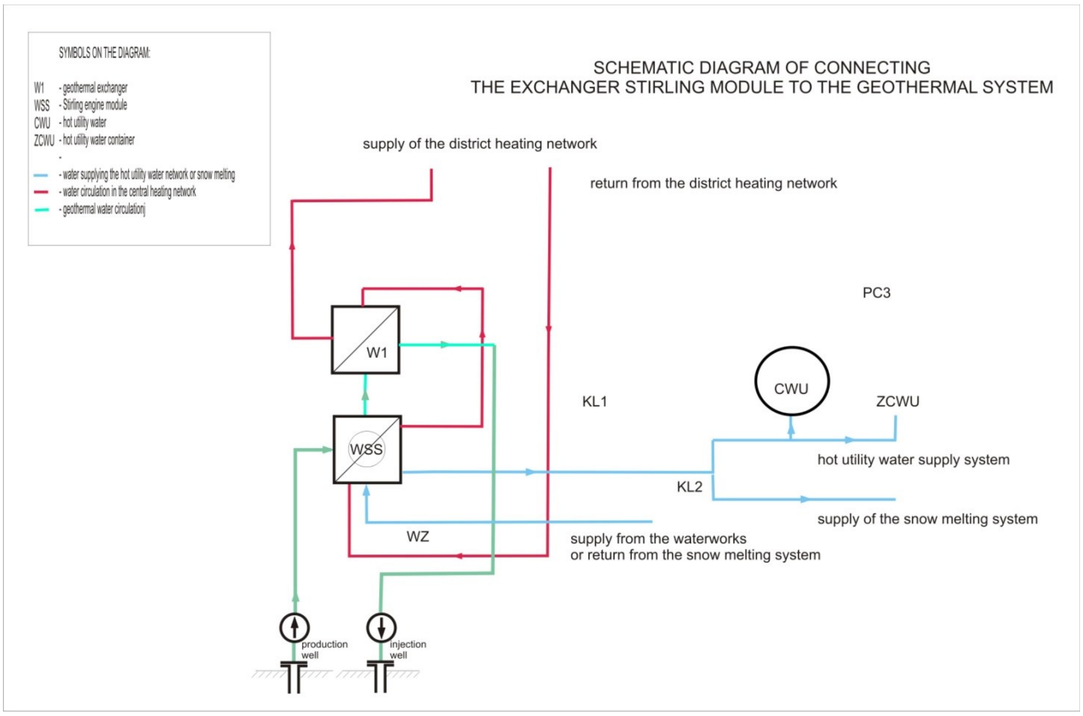

Figure 4: Schematic diagram of the way of connecting the Stirling engine module to the geothermal system.

REFERENCES

Recknagel, Spreinger, Schramek: Ogrzewnictwo, wentylacja, ciepła woda, chłodnictwo, ISBN: 9788392683360 Omni Scala, Wrocław 2008

Szargut, J.: Termodynamika, ISBN: 83-01-13086-5 Wydawnictwo Naukowe PWN Warszawa 2012

Szargut, J.: Teoria Procesów Cieplnych, ISBN: Wydawnictwo Naukowe PWN Warszawa 1973

Żmujdzki, St.: Silniki Stirlinga, ISBN 83-204-1640-X, WNT Warszawa, Poland 1998.