POWER GENERATION FROM LOW ENTHALPY GEOTHERMAL RESOURCES

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Abstract - This paper presents the use of low enthalpy geothermal reservoirs for electric energy production using the Rankin and Kalina cycles. Studies are made to highlight differences between the two cycles, and also to study in detail the cycle with a higher efficiency. Romania was one of the first contries of the European Union which transposed into its national legislation the provisions of Directive 2001/77/EC regarding the production of electric energy from renewable energy sources.

Key words: Geothermal energy, low enthalpy, Kalina, Rankine

1. INTRODUCTION

Geothermal resources have the potential of contributing significantly to sustainable energy use in many parts of the world. The production capacity of geothermal systems is quite variable and different systems respond differently to production, depending on their geological setting and nature. Therefore, comprehensive management is essential for the sustainable use of all geothermal resources.[3]

Electricity from geothermal energy had a modest start in 1904 at Larderello, in the Tuscany region of North-West Italy, with an experimental 10 kW-generator. Today, this form of renewable energy has grown to 8,771 MW in 25 countries, producing an estimated 54,793 GWh/yr. In the beginning of the 19th Century, the Larderello chemical industry came under the direction of Prince Piero Ginori Conti. He experimented with the use of geothermal steam as an energy source for electrical production. He used a piston engine coupled with a 10-kilowat dynamo; the engine was driven by pure steam produced in a small heat exchanger fed with wet steam from a well near Larderello (Figure 1).

This engine used an “indirect cycle”,that is the geothermal fluid heated a secondary pure water to produce steam that moved the piston generator set. This was the first binary cycle using a secondary working fluid. The “indirect cycle” protected the piston from the potential harmful effects of chemicals in the geothermal fluid.[3]

Fig. 1. Prince Ginori Conti and the 10-kW experimental power plant, Larderello, Italy, 1994 (courtesy of ENEL).

Figure 2 illustrates the first commercial geothermal power plant from Larderello (1913), with a 250 kW installed power. Figure 3 presents the geothermal power plant from Larderello today.

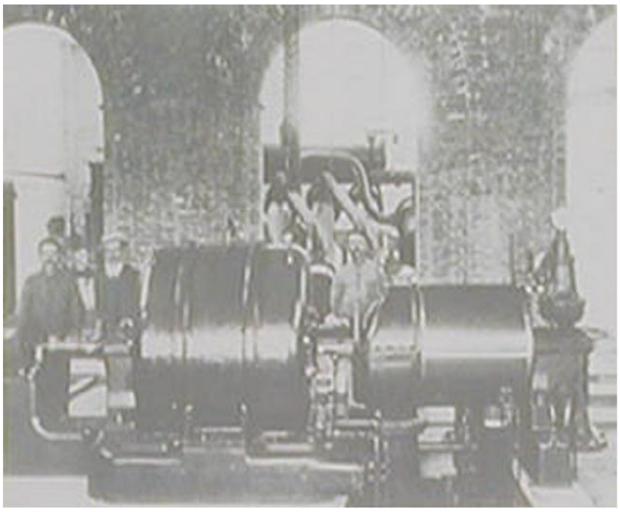


Fig. 2. First commercial geothermal power plant, 250 kW, Larderello, Italy, 1913

Fig.3. Geothermal power plant at Larderello today (courtesy of ENEL).

2. GEOTHERMAL RESOURCES OF BIHOR COUNTY

The search for geothermal resources to be used for energy purposes began in the early 60's, based on the geological research program for hydrocarbon resources [5]. At present, there are over 250 wells drilled in Romania, with depths down to 3,500 m, that show the presence of low enthalpy geothermal resources (40-120°C). The proven reserves, with the already drilled wells, are estimated at about 200 PJ. The main geothermal reservoirs are located in Oradea, Bors, Beius, Western Plain, Otopeni, and Olt Valley, their locations being shown in Figure 4. [5]

Fig. 4. Location of Romanian geothermal reservoirs

Oradea is one of the Romanian towns that, in the production of thermal energy, uses renewable sources to supply energy to households, private companies and public institutions. Oradea Transgex Company supplies space heating and hot tap water using geothermal energy.The price of energy that Oradea and Beius benefits of, is lower than the price resulting from power plants useing conventional sources of energy. A major advantage of using renewable energy sources is that there are no direct emissions of greenhouse gases.These emission occur in the production of used equipment and in the usage of natural gas boilers [5]

The Oradea geothermal reservoir is located in the Triassic limestones and dolomites at depths of 2,200-3,200 m, on an area of about 75 km^2, and it is exploited by 14 wells, of which one is used for reinjection. Well head temperatures range from 70 to 105°C. There are no dissolved gases, and the mineralisation is lower than 0.9-1.2 g/l. The water is of calcium-sulphate-bicarbonate type. The water is about 20,000 years old and the recharge area is in the Northern edge of the Padurea Craiului Mountains and the Borod Basin. The natural recharge rate was calculated at 310 l/s based on the only interference test by now, carried out in 1979 (Paal, 1979). The Oradea aquifer (Triassic) is hydrodynamically connected to the Cretaceous aquifer Felix Spa (shallower and colder), and both are part of the active natural flow of water.[5]

The Bors geothermal reservoir is situated about 6 km north-west of Oradea. This reservoir is completely different from the Oradea reservoir, although both are located in fissured carbonate formations. The Bors reservoir is a tectonically closed aquifer, with a small surface area of 12 km^2. The geothermal water has 13 g/l TDS, 5 Nm^3/m^3 GWR, and a high scaling potential. The dissolved gasses are 70% CO_2 and 30% CH_4. The reservoir temperature is higher than 130°C at the average depth of 2,500 m. The artesian production of the wells can only be maintained by reinjecting the whole amount of extracted geothermal water. In the past, three wells were used to produce a total flow rate of 50 l/s, and two other wells are used for reinjection, at a pressure that did not exceed 6 bars. The geothermal water was used for heating 12 ha greenhouses. The dissolved gasses were partially separated at 7 bars, which was the operating pressure, and then the fluid passed through heat exchangers before being reinjected.

The Beius geothermal reservoir is situated about 60 km south-east of Oradea. The reservoir is located in fissured Triassic calcite and dolomite 1,870–2,370 m deep. The first well has been drilled in 1996, down to 2,576 m. A line shaft pump was set in the well in 1999, now producing up to 45 l/s geothermal water with 84°C wellhead temperature. A second well has been drilled in early 2004, and a line shaft pump has been installed soon after completion. The geothermal water has a low mineralization (462 mg/l TDS), and 22.13 mg/l NCG, mainly CO_2 (0.01 mg/l of H_2S). At present, the geothermal water from the first well is used to supply district heating to part of the town of Beius.[5]

3. THE KALINA CYCLE

In the Kalina cycle, heat at low temperature is transferred indirectly to a circulating fluid [1]. Fig. 5 shows a schematic diagram of the Kalina cycle power plant. The working fluid is a mixture of ammonia and water. The ammonia–water mixture has a varying boiling and condensing temperature. During evaporation, the mixing ratio of the binary working fluid changes because of the lower boiling temperature of ammonia which evaporates predominantly.[1]

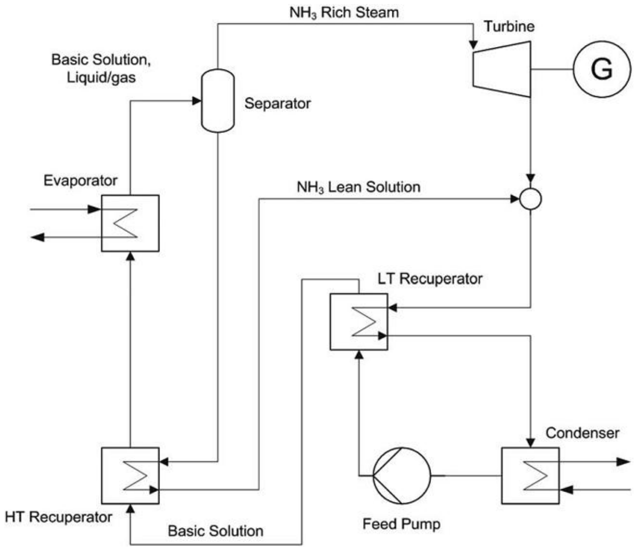


Fig. 5. Kalina cycle process – schematic diagram

In Fig. 6, the different curves present the variable boiling temperatures of different ammonia–water mixtures against the isothermal evaporation of pure water at a pressure of 30 bar.[1]

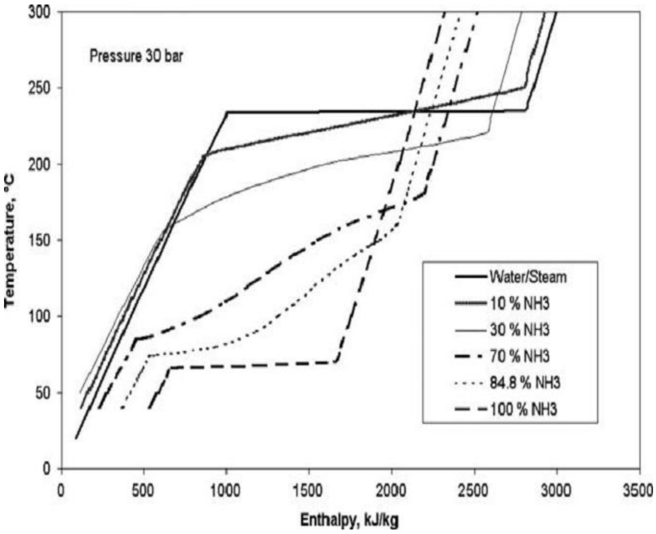
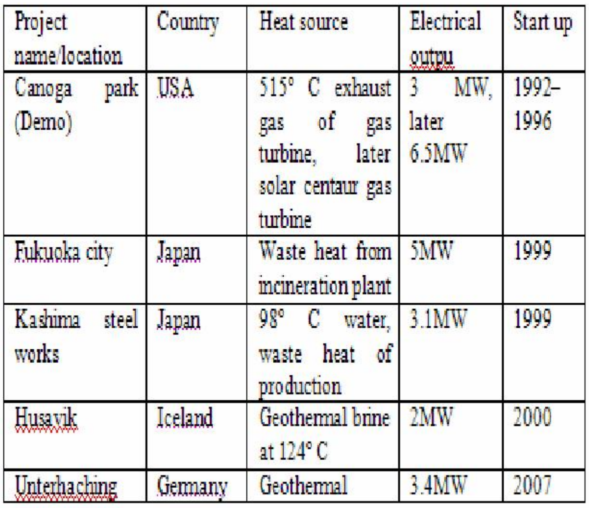


Fig. 6. Comparison between boiling of pure water and different ammonia–water mixtures at 30 bar

The mixture of ammonia and water boils at a variable temperature depending on its composition. The evaporation and condensation processes are not isothermal. The higher the fraction of ammonia in the mixture, the lower is its boiling temperature. With the increasing ammonia concentration, the specific enthalpy of steam decreases.[1]

Before the turbine, the ammonia-rich steam is separated from the liquid phase in a separator. Afterwards, the ammonia-rich steam passes through the turbine. The generator, coupled to the turbine, produces electricity. The molecular weight of the ammonia (17 kg/kmol) is close to that of the water (18 kg/kmol) and therefore it is possible to use normal back-pressure turbines. The turbine needs no special materials for the ammonia–water mixture[1].

Table 1. Kalina projects worldwide



Project name/location	Country	Heat source	Electrical outpu	Start up
Canoga park (Demo)	USA	515° C exhaust gas of gas turbine, later solar centaur gas turbine	3 MW, later 6.5MW	1992–1996
Fukuoka city	Japan	Waste heat from incineration plant	5MW	1999
Kashima steel works	Japan	98° C water, waste heat of production	3.1MW	1999
Husavik	Iceland	Geothermal brine at 124° C	2MW	2000
Unterhaching	Germany	Geothermal	3.4MW	2007

After the turbine, the steam and liquid phases are merged together and condensed in the condenser. Because of the change in the mixture ratio, the evaporation temperature increases continuously in the wet-steam region while it decreases during condensation.

The low temperature (LT) and high temperature (HT) regenerators use the internal residual heat within the cycle. The efficiency is improved with these regenerators. Worldwide, there are only a few power plants working on the Kalina cycle. The best known are given in Table 1.

4. RANKINE CYCLE FOR ELECTRICA ENERGY PRODUCTION

The Organic Rankine Cycle (ORC) is a cycle that uses an organic work fluid instead of steam [8]. In the last years, it had become a popular production process for electric energy thanks to the fact that it offers the possibility of using heat resulting from low energy and temperature levels. Figure 7 presents the main components of a power plant using the Rankine cycle and figure 8 presents the T-S diagram of the cycle itself [2][8].

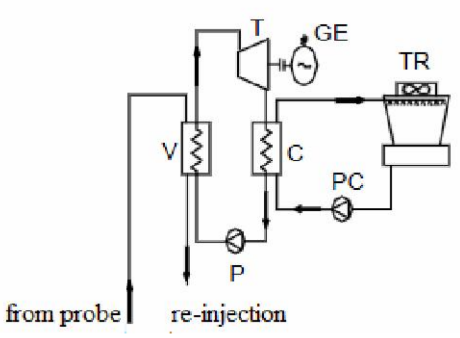


Fig.7. Rankine cycle power plant with secondary fluid

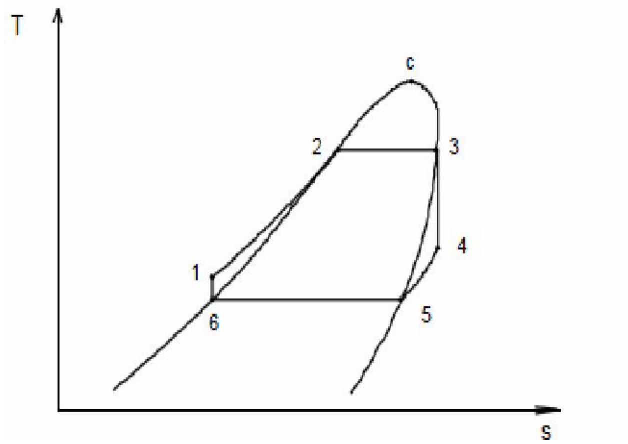


Fig.8. The Rankine cycle for the secondary fluid

Binary systems with conventional Rankine Cycle use a secondary working fluid. In the evaporator (V), the working fluid is heated from state 1 to the saturation temperature (state 2), and evaporates (state 3), taking heat from the primary thermal agent, which can be both geothermal fluid resulting from a low or medium production well, or wet steam resulting from the expansion of dry saturated steam in a backpressure steam turbine . The dry saturated vapour (state 3) enters the turbine that drives the electric generator. After exiting the turbine, the overheated vapour (state 4) cools down to saturation temperature (state 5) and condensates (saturated liquid, state 6) giving heat to the cooling water. The cooling water is usually cooled down in a dry or wet cooling tower, when not enough cold water is available from another source. The pump compresses the saturated liquid (state 6) to vaporization pressure (state 1).[1][8]

As secondary working fluid, hydrocarbons or refrigerants (CFC's or HCFC's) are generally used. By choosing the proper secondary working fluid, binary systems can work with thermal agents using temperatures between 85 and 170°C. The upper limit depends on the thermal stability of the secondary fluid, and the lower limit is determined mainly by practical and economical limitation of the heat exchangers size. The usage of organic fluids has many advantages over water use in low temperature Rankine cycles, for example:[8]

* The thermal efficiency of cycles using organic fluids is higher than the efficiency of cycles using water in the same temperature limits. The main advantage of organic fluids is that it can take more heat from the geothermal fluid than water. Consequently, though the two working fluids thermal efficiencies have close values, the value of the global efficiency proportional with the produced electric energy is considerable higher is case of organic fluid use.

* The organic fluid exits the turbine as overheated vapour, not as saturated wet vapour, as water, so it decreases the turbine blades erosion. Part of evacuated heat can be recovered with a supplementary cost, and can be used to preheat the liquid to enter the vaporizer.

* The enthalpy drop is sufficiently low for a one stage turbine with high efficiency

* For a given power, the organic fluid flow rate is higher, the equipment size is small, the vapour density is higher, and the volume flow rate is smaller as compared to water.

* The organic fluids pressure is higher than the atmospheric pressure, on the whole cycle, therefore air entering the machine is impossible. On the other hand, even if it is not toxic and flammable, the organic fluid needs a perfectly tight installation, which makes its construction and service complicated.

The majority installations using secondary fluids are small modular units with powers that vary from hundreds of kW to a few MW. These have a satisfying economic efficiency, because modular construction reduces installation time and costs. Larger power installations are obtained using a number of modular units[8].

5. CASE STUDY

The Kalina - type cycle that we consider here is of a simplified and modified version for analysis purposes, in the way that the distillation and condensation units are replaced with a resorber. This is made in order to get a consistent comparison in terms of system complexity: that is, all the compared systems have the same number of four components. [7]. This cycle is illustrated in Fig. 10, and as it can be observed, it has rather low energy efficiency, even though the exergy efficiency is the same as that of the ORC from Fig. 9

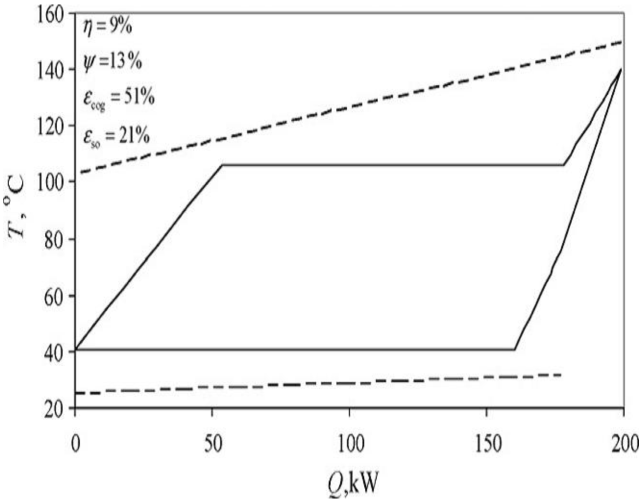


Fig. 9. The ˙–T-Q diagram of the Organic Rankine Cycle (ORC) with R21.

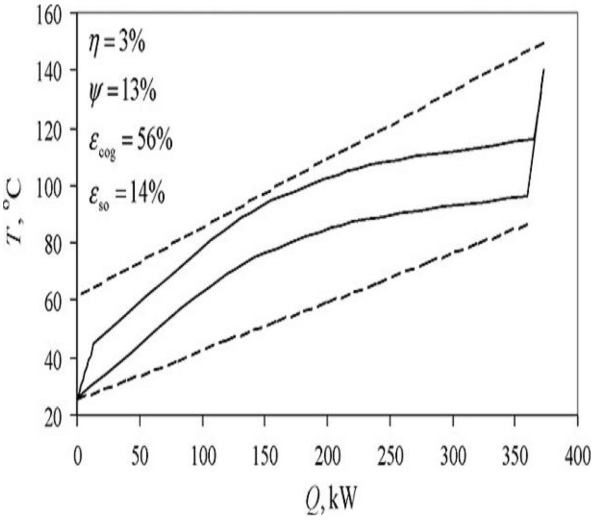
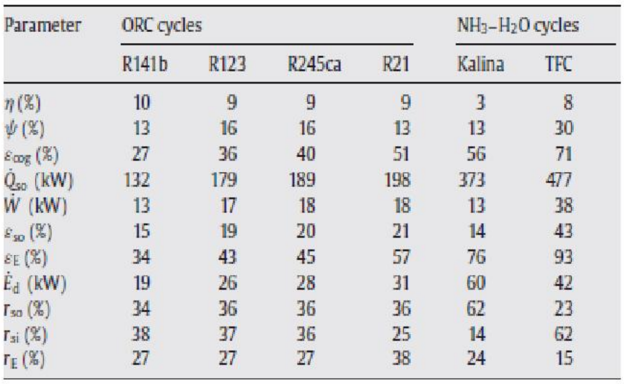


Fig. 10. The T-Q diagram of the Kalina-type ammonia–water cycle.

The results of this comparative analysis are presented in Table 2, that includes a series of relevant parameters as to be explained here.[7]

Table 2 Performance comparison among various cycles



Parameter	ORC cycles				NH_3–H_2O cycles	
	R141b	R123	R245ca	R21	Kalina	TFC
η (%)	10	9	9	9	3	8
ψ (%)	13	16	16	13	13	30
ε_{cog} (%)	27	36	40	51	56	71
$\dot{Q}_{so}$ (kW)	132	179	189	198	373	477
$\dot{W}$ (kW)	13	17	18	18	13	38
ε_{so} (%)	15	19	20	21	14	43
ε_E (%)	34	43	45	57	76	93
$\dot{E}_d$ (kW)	19	26	28	31	60	42
r_{so} (%)	34	36	36	36	62	23
r_{si} (%)	38	37	36	25	14	62
r_E (%)	27	27	27	38	24	15

Surprisingly, the cycle that we propose here, denoted with "trilateral" in Table 2, features an energy efficiency of 8% as compared to the ORC–R141b that displays the highest efficiency of 10%. This is only apparently a drawback, because in our case study the cycle with maximum energy efficiency delivers the least work, as it will be shown below. The trilateral flash cycle (TFC) features, however, a two times larger exergy efficiency than all other options [7].

Moreover, TFC cogeneration effectiveness is the highest as 71%; the second largest one is for Kalina-type cycle, and the smallest is obtained for the R141b. This demonstrates that the cycle with the highest energy efficiency recovers inefficiently the heat from the source. In Table 2, we also show the heat rate extracted from the source in all cases for comparison purpose to demonstrate how much comes from each one. The results indicate that the R141b cycle extracts the least heat from the source as 132 kW, while the trilateral flash cycle receives the most, 3.6 times more than that as 477 kW. This is due to the fact that the TFC uses the most of the source's exergy because both the source fluid (water) and the working fluid (ammonia–water) are in liquid state and have similar specific heats, and thus the temperature difference in the heat exchanger is minimized. However, there is not the some case for any of the ORC cycles: they can recover at most 40% (R21 case) from the amount of heat recovered by the TFC.[7]

This reality clarifies why, from all the studied cases, the trilateral flash cycle with 8% energy efficiency delivers the maximum amount of work at the expander shaft (38 kW), as compared to 13 kW delivered by the R141b-cycle with 10% energy efficiency.

CONCLUSIONS

In the production of electric energy from geothermal sources, Kalina and Rankine cycles are two frequently used methods [6]. The two cycles are very alike, Kalina cycle being an improvement of the Rankine cycle, and have the following differences:[6][8]

- variable boiling temperature: The 85% ammonia – water mixture allows a variable temperature process in a conventional boiler. At a 31.2 bar presure, the working fluid starts boiling at 74ºC and overheats at 149ºC. This process produces a very good working fluid.
- ciclu recuperativ înalt
- high recovery cycle: The recovery heat exchangers (regenerators) provide about 38% of the overall heat transferred to the working fluid, improving the efficiency. Using mixtures makes it possible to transfer heat from 9.2 bars exiting the turbine to 31.2 bars of the working fluid; the turbine exiting pressure is lower than the one from the boiler, the temperature at which the exiting steam starts to condensate is 35ºC higher than the boiling temperature of the working fluid By contrast,the turbine exhaust of binary installations that work with organic fluids,these can not be used for boiling. For a low quantity of evacuated steam used to preheat the liquid, recovery is limited.[6]

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