Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

New Concepts for Power Generation Necessary

Gerold Göttlicher, Pascal Schlagermann

EnBW Energie Baden-Württemberg AG, Durlacher Allee 93, 76131 Karlsruhe, Germany

g.goettlicher@enbw.com, p.schlagermann@enbw.com

Keywords: low enthalpy cycles, power cycle optimization, geothermal power

ABSTRACT

Present geothermal power cycle for low enthalpy geothermal fields (utilizing brine not steam) attain electrical efficiencies far from the ideal carnot factor and therefore are not well utilizing the expensive geothermal wells. This is to a large part due to excessively high exergy losses in heat transfer from the geothermal water to the steam of the turbine process, sometimes visible in a drastically reduced temperature reaching the turbine entrance. These exergy losses could be widely reduced by methods which have long been applied in other heat recovery processes for electricity. Also a new power cycle is presented, which minimizes these losses.

These measures are presented in order to stimulate the awareness for thermodynamics and the development of such improved power systems. Furthermore this would contribute to the reduction of electricity cost.

1. INTRODUCTION

Geothermal power projects in Germany and France suffer from low electrical efficiency due to temperatures restricted to below 200°C. This temperature limits the potential of the physical law of the Carnot factor, which rises with temperature. Current projects in operation, construction or exploration have to utilize hot brines and cannot access direct geothermal steam. While high costs are spent for the geothermal wells, the operating plant exhibit extremely high exergy losses sometimes even easily visible by dramatic temperature losses from well to turbine inlet. Optimized heat recovery has already been developed in heat recovery steam cycles behind gas turbines which can be taken as a reference for improvement options. These are mainly focussing on reducing the exergy losses in heat exchanging from heat source to the working fluid, e.g. by multiple steam pressures, multiple cycles with different working fluids or novel processes. As geothermal heat has to be regarded as high value product due to expensive exploitation, the additional cost expense for applying thermodynamic optimized processes might have a good economic chance.

2. THERMODYNAMIC PRINCIPLES AND LIMITS

The theoretically maximum attainable efficiency of thermal power cycles is represented by the Carnot factor, which states that with increasing process temperature above the environmental temperature the fraction of usable energy is increasing:

$$carnot\_factor = 1 - \frac{(lower\_process\_temperature)}{(upper\_process\_temperature)} \leq 1 \qquad (1)$$

Figure 1 gives an overview on the theoretical Carnot factor and the range of real efficiencies of different power generation processes. Temperatures available from geothermal brines are in general much lower than temperatures attainable by combustion and therefore show a much lower efficiency potential. One option to increase the Carnot factor in a geothermal power plant would be to increase the temperature by making the geologists drill deeper. This, however is only a limited solution. Additionally power cycles have to be adapted to minimize exergy losses from the well to the generator.

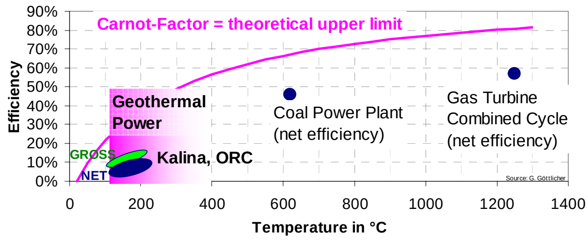

Figure 1: Efficiencies and ideal Carnot factors of different power generation cycles and processes in dependence of the process temperature

The ideal efficiency represented by the Carnot factor is reduced to the real cycle efficiency due to a number of influences like temperature losses in heat transfer, friction losses, leakage losses, heat losses and other losses. For a high efficiency besides the principle to aim for high temperatures it is also essential to avoid exergy losses in heat transfer from the geothermal brine to the turbine working fluid. This means that according to the second law of thermodynamics it is not sufficient to transfer all energy to the turbine without energy losses, but also to especially care for a maximized mean temperature of heat transfer from brine to working fluid. Exergy losses ΔE in heat transfer can be expressed by:

$$\Delta E = \int T_{ambient} \frac{T_{Brine} - T_{working\ fluid}}{T_{Brine} \cdot T_{working\ fluid}} dQ \qquad (2)$$

Drawing the Carnot factor of the heating and cooling curves over the amount of heat transferred shows the exergy losses as the area between the heating curve of the working fluid and the cooling curve of the geothermal brine (Figure 2). To reduce these losses the gap must be minimized.

In any case the efficiency of a real process is lower than the Carnot factor and therefore it is always limited by the upper process temperature.

It is one of the advantages of ORC and Kalina cycles compared to water steam cycles that the exergy losses in heat transfer to the working fluid can be reduced. Due to evaporation at floating temperature with Kalina cycles the heating and cooling curves even come closer than with ORC cycles. Figure 3 shows a qualitative comparison of the heating curves of ORC and Kalina process which can e.g. also be found in [Mirolli]. The area representing the exergy losses between the heating curve of the Kalina process and the cooling curve of the brine is smaller than those between ORC heating curve and brine and thus exergy losses are smaller.

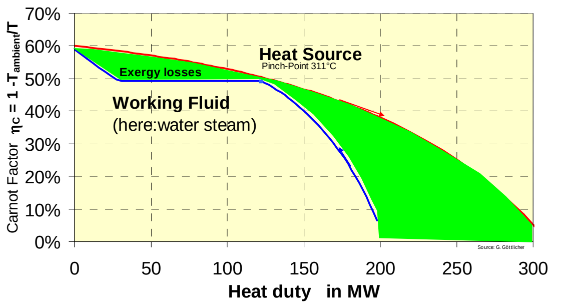

Figure 2: Exergy losses in heat transfer from heat source to working fluid

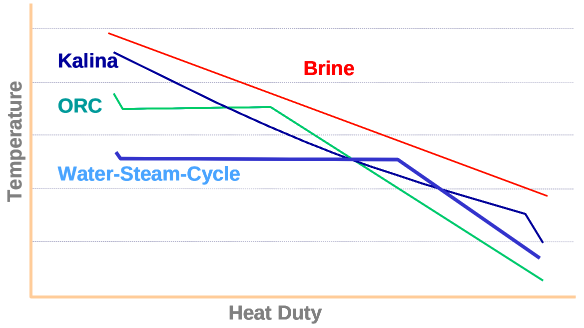

Figure 3: Qualitative comparison of heating curves for Kalina and ORC

Parameters like pressure ratios in the cycle, degree of superheating, regenerative preheating or recuperation have been varied to reduce efficiency losses [Köhler]. However, dividing the power generation in several evaporation pressure steps has not been applied yet in geothermal cycles.

3. STATE OF THE ART OF GEOTHERMAL POWER

All geothermal power plants in Germany utilize low enthalpy brines showing efficiencies below 10%. If geothermal power in future won't rely on heat sales at large scale the low electric efficiency will be a significant limit for its potential application.

One forward-looking project is in Soultz-sous–Forêts in France, where a lot of emphasis is put on research in the geothermal heat exchanger. The temperature in a depth of around 5000 m is around 200°C. At the well head the brine temperature is already reduced to 175°C due to geological disturbances (Figure 4). After heat transfer and evaporation of the organic working fluid only 128°C are reaching the turbine inlet. The Carnot factor in this case is reduced by almost one third from 37% in the ground to 33% at the well head and 26% at the turbine. This means a reduction of the Carnot factor compared to the potential underground by 10% until reaching the well head and additional 21% from well head to turbine inlet. Furthermore the brine is cooled down to only 70°C before it is sent back to the ground. This again means a loss of 31% of the Carnot factor. Excluding the geological process this means a loss of Carnot potential referring to the geothermal brine of 52% or 19 percentage points of efficiency. At the same time this not utilized temperature potential also indicates the chances to improve the brine utilization.

Considering the specific geological conditions on this site, already a drilling depth of 1500m would have been sufficient to gain a 128°C brine temperature– meaning that 3500m of drilling depth are wasted in an idealized thermodynamic view. Although there are physical and technical reasons for not utilizing the temperature potential, this example impressively shows the potential for improvements of the rather simple system available presently.

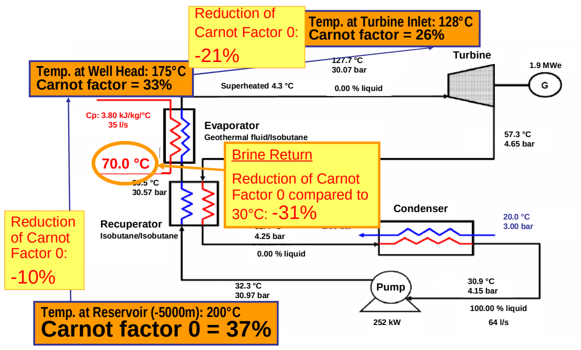

Figure 4: Flow and temperature scheme of the geothermal project in Soultz-sous-Forêts [Cuenot]

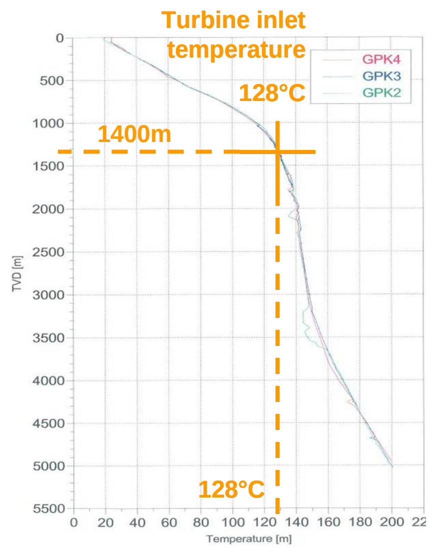

Figure 5: geothermal temperature profile

4. STATE OF THE ART OF HEAT RECOVERY POWER GENERATION

A very good example of efficient waste heat recovery are the waste steam generation power cycle as bottoming cycles of gas turbines, which have systematically been optimized. The main reason is to utilize an expensive fuel efficiently and thereby economically. Only together with highly efficient bottoming steam cycles modern gas turbines in a combined cycle can attain electrical efficiencies close to 60%.

Additionally to optimizing steam temperatures and pressures the most important measure to reduce the exergy in heat transfer by reducing the "gap" between heating and cooling curve is to evaporate steam at different pressure levels.

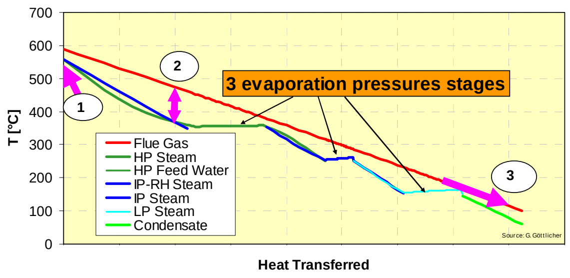

Figure 6: Reduction of exergy losses by multiple pressure heat recovery steam generators

Figure 6 shows the most important effects to improve efficiency and heat utilization by multiple pressure heat recovery steam generators:

1. minimize the temperature loss at the turbine inlet, maximize the upper temperature of the working fluid
2. reduce gaps between the heating curve of the working fluid and the cooling curve of the brine
3. minimize the lower temperature of the waste heat (flue gas or brine) in order to exploit a maximum share of the available heat. This is required in addition to the minimization of the cold end (condenser) temperature of the power cycle and is achieved partly by multiple pressure levels, multiple cycles with different working fluids or e.g. circulation of condensate.

5. DEVELOPMENT OPTIONS IN GEOTHERMAL POWER

EnBW is participating in the geothermal power plant projects in Soultz-sous-Forêts, Basel and Bruchsal. EnBW is starting up a Kalina power plant at the hydrothermal geothermal power plant in Bruchsal. With this cycle the exergy losses in heat transfer can be reduced. But still the temperature span of cooling the brine is by far not yet used, sending back the brine at around 60°C. Efficiencies in all projects are not satisfactory.

A new alternative process development supported by EnBW is a power cycle applying a triangular process, which shall optimize the waste heat utilization to the edge where the brine cooling curve and the heating curve of the working fluid are in parallel, thereby reducing the exergy losses in heat transfer to a minimum [Löffler]. This cycle will rely on flashing hot water into an expanding cylinder of a reciprocating engine. Although the cycle efficiency i.e. the ratio of heat input to electricity output is in the same order as for a Clausius-Rankine cycle more of the heat of the brine can be transferred to the cycle. As a result the overall efficiency of the triangular process considering the available heat source is much higher. The machine is still under development where costs and feasibility need to be proven, but thermodynamic calculation show efficiency improvement of more than 70% compared to water steam cycles (Table. 1).

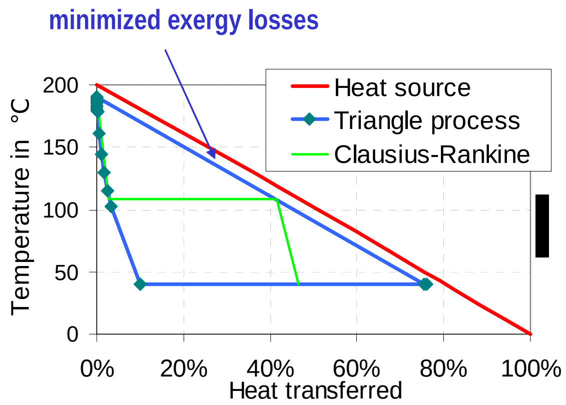

Figure 7: Heating curves of triangular cycle

Table. 1: Thermodynamic evaluation of triangular cycle and water steam cycle

Process parameters		
Heat source temperature	175°C	
Heat power	741kW	
Pinch	10K	
Condenser	40°C / 0.07 bar	
Expansion pressure ratio p_1/p_{cond}	94	
Reference Rankine cycle: evaporator pressure	1.4bar	
Isentropic efficiency	70%	
Process Comparison		
	Triangular Cycle	**Clausius-Rankine**
Cycle efficiency	**11.2%**	**12.7%**
Brine enthalpy transferred to cycle	76%	47%
Overall efficiency from heat to electricity	11.3%	6.2%
Electric Power	60kW	33 kW

6. COST PERSPECTIVES

Drilling costs of German low enthalpy projects have a much higher share of the total initial investment than in geologically more favourable regions. From compilation of literature data and project experience at typical German conditions the investment shares of main sections of a geothermal power plant can be estimated to be at around 60% to 65% for the geothermal well including planning for the drilling, at around 15% to 20% for the geothermal loop including the production pump and at around 20% to 25% for the binary cycle (Figure 8).

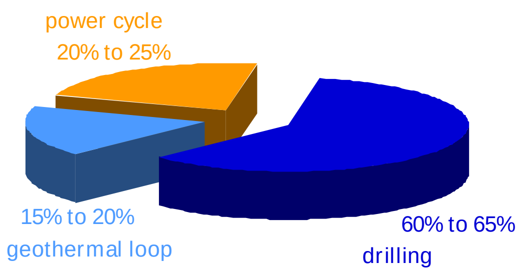

Figure 8: Typical share of investment for a hydrothermal geothermal power projects in Germany

It has been shown above, that the Carnot potential is largely not utilized. If the power cycle could be improved, only one quarter of the initial investment of the overall project (Figure 8) has to be touched or increased, with the chance to economically improve the overall project.

To illustrate this effect, it is assumed, that the efficiency of the power cycle is improved by 20%. How much can be invested for this improvement for the same economy? (Table. 2) shows the basic assumptions for this estimation. The base case of this example considers a hydrothermal geothermal power project in Germany applying an ORC with an electrical gross output of 2.2 MW without heat sales. The drilling depth of 3,500m with a brine flow of 216m³/h at 150°C is equivalent to a temperature gradient of 4.3K per 100m which is typical in the region of the upper Rhine valley.

As a result, for 20% efficiency improvement the investment in the power cycle could be doubled keeping the overall project revenue constant. The total initial investment would increase by 27%. As has been shown above, there is a much larger potential in the utilization of the Carnot factor. This gives rise to the hope for improvements in the energy efficiency and electricity generation costs.

Table. 2: Basic assumptions of an economic case study for 20% increase of electrical efficiency

	Base case		20% improved efficiency	
Drilling Depth	3 500	m	3 500	m
Number of boreholes	2	bore	2	bore
Well flow	60	l/s	60	l/s
Well temperature	150	°C	150	°C
Geothermal heat potential	26 500	kW	26 500	kW
Power plant efficiency	8.5%		10.2%	
Electric power	2252	kW	2703	kW
Annual operating hours	8 000	h/a	8 000	h/a
Project life time	20	years	20	years
Electricty revenue	0.198	€/kWh	0.198	€/kWh
Interest rate	8.0%		8.0%	
power cycle cost	100%		203%	
Initial investment	100%		127%	
Present value	100%		100%	

7. CONCLUSIONS

Geothermal power generation is not sufficiently honoured by only respecting the law of energy conservation. At present geothermal power projects seem very much to be designed in the two halves represented by the geological part and the power generation part. Low efficiency and high cost indicate the requirement of improvement under consideration in the sense of the second law of thermodynamics.

Today only one pressure stage cycles are available for low enthalpy geothermal power plants on the market. This is probably due to the fact that geothermal heat can be cheaply produced in many regions by drilling only 1000 to 2000m with sufficiently high temperatures. Efficiency improvements of the power generation cycle then are not important or may not cost much. As described above the situation in Germany is different: geothermal heat is expensive and efficiency improvement is more valuable. However up to now there are only few plants and obviously the market still is too small to attract a new cycle development. In addition more fundamental problems to operate a geothermal loop are predominant.

If geothermal power shall reach a higher distribution in low enthalpy regions, costs have to be reduced. It has been shown here, that the power cycle has a big potential for better utilization of the investment in an geothermal loop. For this purpose the power generation processes have to be improved. The comparison with gas turbine combined cycles shows a realistic chance for significant improvements of the utilization of the heat source by the development of multiple pressure steam cycles with adapted working fluids as described above. A further potential of efficiency and economy might be exploited by a combined optimization of power cycle, well temperature and well capacity. More investigations on the optimum design will be necessary in projects being explored presently e.g. at EnBW. For suppliers there is a chance to open up an economically sustainable future market by the development of geological power cycles which significantly improve the geothermal power economy.

REFERENCES

Mirolli, Mark D.: Husavik Geothermal Power Plant, 2003

Köhler, Silke: Geothermisch angetriebene Dampfkraftprozesse Analyse und Prozessvergleich binärer Kraftwerke, dissertation, technical university of Berlin, 2005.

Bronicki, Lucien Y.: Advanced Power Cycles for Enhancing Geothermal Sustainability: 1000 MW Deployed Worldwide, IEEE PES General Meeting, USA, July 2008

Cuenot, N.: The European EGS project at Soultz-sous-Forêts: from extensive exploration to power production, EEIG – Deep Heat Mining, 2008

Löffler, Michael: Cycle with Flash Evaporation in the Working Chamber of a Piston Engine, VGB Powertech, July 2007, pp. 92 – 97.