Thermodynamic Modeling of Binary Cycles Looking for Best Case Scenarios

Silke Köhler and Ali Saadat
GFZ-Potsdam, Section Geothermics, Telegrafenberg, D-14473 Potsdam, Germany
Email: skoe@gfz-potsdam.de, saadat@gfz-potsdam.de

Abstract

Power plant design is done with the help of numerical models. For binary power plants using other working fluids than water numerical models were set up and applied on settings describing typical geothermal resources in Germany. Charts come along with the numerical results and aid in understanding the principles of the cycles. Parameter variations show that installation of a geothermal power plant in the North German Basin requires brine temperature above 100°C and that mass flow rates over 50 m³/h are favourable to get to a commercial application.

Keywords: *ORC, Kalina, efficiency, thermodynamic properties, phase diagram, ammonia water mixture.*

1 Introduction

Binary cycles like the Organic Rankine Cycle (ORC) and the Kalina cycle are appropriate to convert geothermal energy to electricity. Since 1980 a number of theoretical analysis were carried out, but information on process parameters and operational data of plants are sparse. Detailed numerical simulations allow a closer look at the inside of the plants, aiming at thermodynamic optimization of the cycles. Plant optimization embraces three fields: plant layout including choice of the working fluid, adjustment of process parameters and dimensioning of equipment and machines. Parametric studies were conducted for both cycles assuming identical, realistic boundary conditions. This paper focuses on the temperature range found in geothermal wells in Germany, i.e. brine temperatures 100-200°C and liquid brine only.

The thermodynamic properties of the working fluids are key parameters for exact modelling of the plants. They are tabulated in reference books, e.g. VDI Wärmeatlas (VDI, 1994), but electronic databases are still sparse. Likewise, charts e.g. T-s plots and comparable diagrams used for visualization and basic understanding of the processes are almost not available. The U.S. National Institute of Standards and Technology (NIST, 2002) supplied a database that allows the user to plot these charts for a limited number of working fluids and Maack and Valdimarsson (2002) were the first to present such a diagram for the Kalina cycle. In the following charts prepared with the NIST database are presented and used to discuss the basic ideas and differences of the cycles.

2 Does thermal efficiency allow proper comparison of geothermal power plants?

Although very often fired by renewable energy sources, binary power plants are close relatives of fossil fuel fired power plants. The major difference is the lower temperature of the heat source and its finite heat capacity. The thermal efficiency of a heat engine is defined as the ratio of the net work developed to the total energy added by heat transfer (Bejan et al., 1996). It is given by:

$$\eta_{cycle} = \frac{w}{h_1 - h_2} \qquad (1)$$

where:

η_{cycle}	thermal efficiency of the cycle
w	work extracted from the cycle kW/kg
$h_1 - h_2$	heat transferred to the engine kW/kg

This approach is insofar appropriate, as one aims at comparing different cycles or settings running with identical heat input. In geothermal power plants this is the amount of energy extracted by cooling the brine from the initial temperature down to the return temperature. In most cases neither the initial temperature of the brine nor the heat input are the same and thermal efficiency alone does not allow proper comparison. From our point of view overall efficiency is a suitable figure of merit for comparison of different plants and cycles as well as for sensitivity analysis. It still does not take into account that the quality of the heat source depends on the source temperature, but it is easier to understand than the second law (or exergetic) efficiency and therefore especially useful in an interdisciplinary environment.

Generally spoken efficiency of a plant is nothing but the benefits divided by the expenses. The overall efficiency of a geothermal power plant needs to allow for the parasitic loads i.e. cooling system and feed pump as well as down hole pump and other electrical equipment. So the benefit of the geothermal power plant at design conditions is the net capacity.

To compare different plants or designs using the same heat source and not underlying any conditions concerning the return temperature, the efficiency needs to consider the total expenses, that is the energy content of the brine. Therefore a point of reference has to be determined. The environment, indicated by T_0 in equation (2), is a handy reference state, since it will be used for calculation of the exergy content as well. In this general set-up, the overall energetic efficiency of a plant using geothermal brine is:

$$\eta_{plant} = \frac{P_{net}}{\dot{m}_b c_b \left(T_b - T_0\right)} \qquad (2)$$

where

η_{plant}	overall efficiency of the plant
P_{net}	net capacity kW
$\dot{m}_b$	mass flow rate brine kg/s
c_b	specific heat capacity brine kJ/kg °K
T_b	temperature of the brine °K
T_0	temperature of the environment °K

Setting the energy content of the brine as denominator, we get a measure for the quality of a geothermal power plant similar to the efficiency of e.g. a coal fired power plant, where the overall efficiency relates to the lower heating value. Analogous to coal fired power plants the whole system can be split in subsystems with an individual efficiency assigned to the each subsystem.

3 Organic Rankine Cycles (ORC)

The all-purpose ORC is a simple Rankine cycle, using an organic working fluid. Recuperation is possible, but most of the existing plants make no use of it. Figure 1 illustrates the cycle in a flow chart.

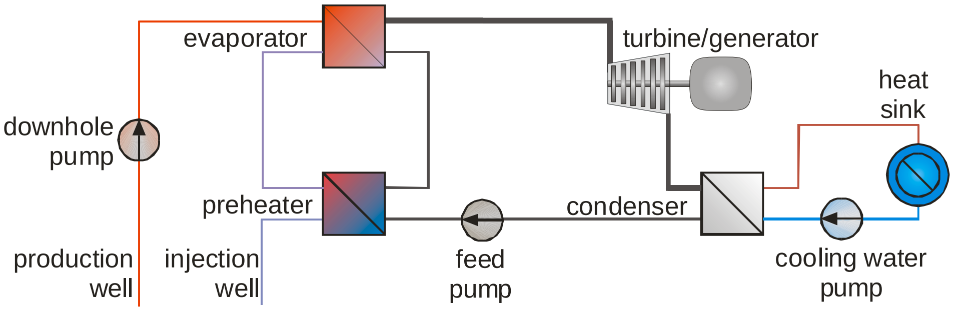


Figure 1: Flowchart of a simple organic Rankine Cycle (ORC).

Figure 2 shows the temperature-entropy diagram of butane with pumping (1-2), preheating (2-3), evaporation (3-4), expansion (4-5), desuperheating and condensing (5-1). The data refers to a case study carried out by Köhler (2002) and was calculated with help of the CycleTempo software (Delft University of Technology, 2000). The work is extracted while the fluid expands in the turbine. The quantity of work is the drop of specific enthalpy from point 4 to 5 and finds its figurative expression in the length of the line 4-5 in Figure 2. To elongate the line and get more specific work at given cooling conditions, that is point 5 is fixed, the evaporation temperature and therefore evaporation pressure needs to be raised. Due to the limited heat capacity of the source, the mass flow rate in the plant has to decrease at increasing evaporation temperature. The actual amount of work is the specific work times the mass flow rate. Thus an optimum evaporation temperature where the work output of the turbine reaches a maximum is expected. These relations are presented in Figure 3. At increasing evaporation temperature the specific enthalpy drop increases as well as the thermal efficiency of the cycle while the mass flow rate decreases. At 95°C maximum work is extracted. This is the maximum power point and the optimum evaporation temperature for the specific setting.

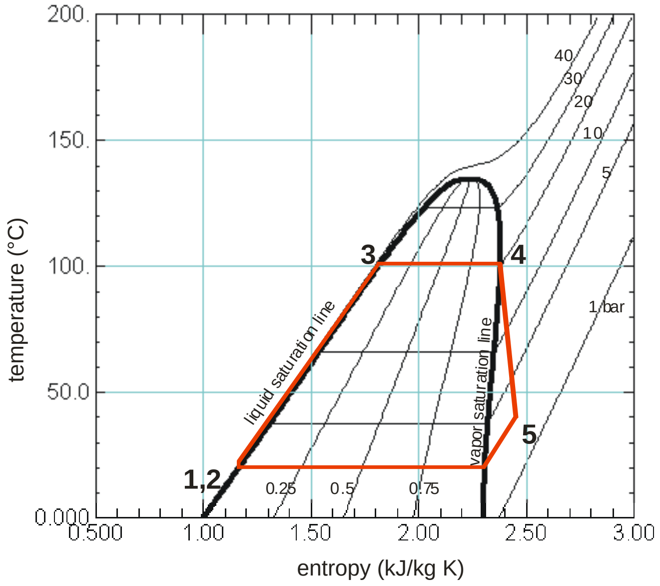


Figure 2: Temperature-entropy diagram of i-butane with simple Rankine cycle. Thermodynamic properties of the fluid according NIST (2002), calculation of the cycle made with help of CycleTempo software (Delft University of Technology, 2000).

Due to the strong influence of brine temperature, cooling conditions, mass flow rate of the brine and capacity of the down hole pump (resulting from reservoir characteristics) net capacity depends strongly on the specific site. Figure 4 and

Figure 5 refer to a case study in the North German Basin carried out by Köhler (2002). They address parameter studies for source temperature, sink temperature and mass flow rate of the brine. The water level in the well was assumed at 400 m below surface. For every setting the optimal operating conditions were determined by varying process parameters as well as the working fluid.

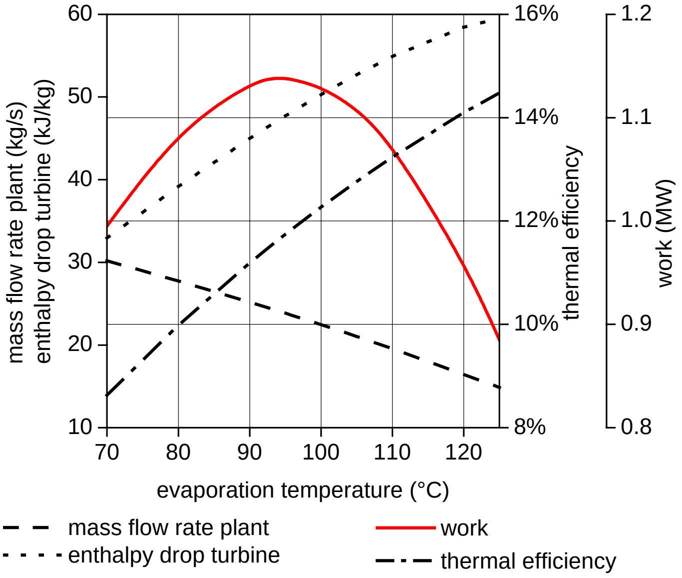
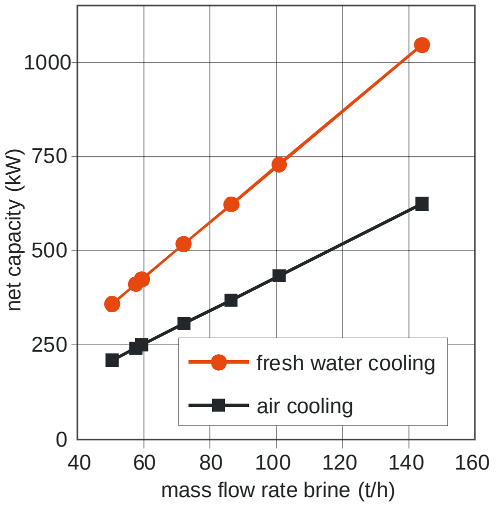


Figure 3: Mass flow rate, enthalpy drop in the turbine, resulting work and conversion efficiency of a binary geothermal power plant (simple ORC). Brine temperature 147°C, mass flow rate of the brine 27 kg/s, working medium i-butane.

Net capacity is a linear function of the mass flow rate of the brine. At 50 m³/h and with air cooling nearly 250 kW_{net} can be generated. This seems a reasonable size to start commercial application of the technology and is a realistic goal in the geological setting. The change from air-cooling to fresh water-cooling may increase the net capacity by 70%. The increase is due to two effects: The better cooling conditions and lower condensation temperature enable significantly higher capacity of the turbine (e.g. at 50 t/h turbine capacity increases from 411 kW to 550 kW) and the lower parasitic loads mainly resulting from the cooling system (33 kW cooling water pump compared to 49 kW fan capacity, both at 50 t/h). The feed pump does not change notably. The down hole pump is not affected by the cooling system.



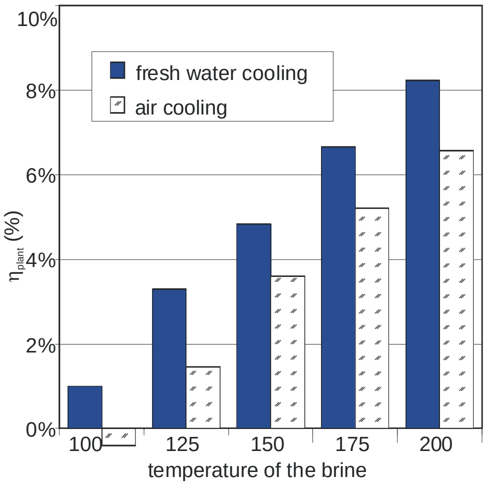


Figure 4: Net capacity of a geothermal power plant. Temperature of the brine 147°C.

Figure 5: Overall efficiency of a geothermal power plant, variation of brine temperature.

The brine temperature in such settings should be clearly above 100°C, otherwise the overall efficiency gets to low (<2 %). In the worst case the efficiency might even become negative. For instance at 100°C brine temperature and air cooling the parasitic loads for the pumps and fans exceed the generator capacity and more power is consumed than produced.

4 Kalina Cycle

The Kalina cycle uses ammonia-water mixture as working fluid instead of a pure fluid. The composition of the mixture is not constant at all states of the cycle. The cycle is basically a Rankine cycle with additional distillation and absorption units.

Maack and Valdimarsson (2002) stated that there is no black magic behind the Kalina technology but pure thermodynamics. However, on the first glance the accumulation of heat exchanging, mixing and separation equipment might be puzzling. Figure 6 shows the flowchart of a typical Kalina cycle. The configuration refers to the set-up as it was installed in Husavik, Iceland.

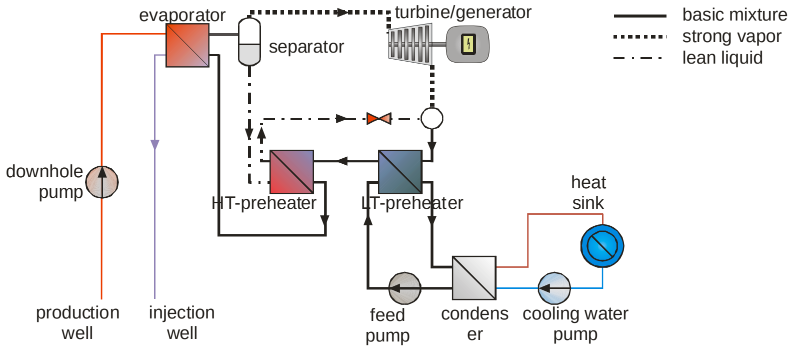


Figure 6: Flowchart of the KCS 34 according to Maack and Valdimarsson (2002).

Phase diagrams help to clear up the picture: Using the mixture, evaporation and condensation both happen at constant pressure but variable temperature. The temperature range depends on the composition of the fluid. At higher ammonia concentration, the temperatures are generally lower (see Figure 7). The pressure drop in the turbine should be high. i.e. power plant design aims at high pressure upstream of the turbine and low pressure in the condenser. The temperature of the heat source and the heat sink limits upper and lower temperatures of the process, respectively. The use of a mixture as working fluid adds one degree of freedom, which allows manipulating the pressure in the system by changing the composition of the mixture. At given cooling conditions the pressure in the condenser may be reduced by decreasing the ammonia concentration of the condensing fluid. Increasing the ammonia concentration may raise the evaporation pressure, at the

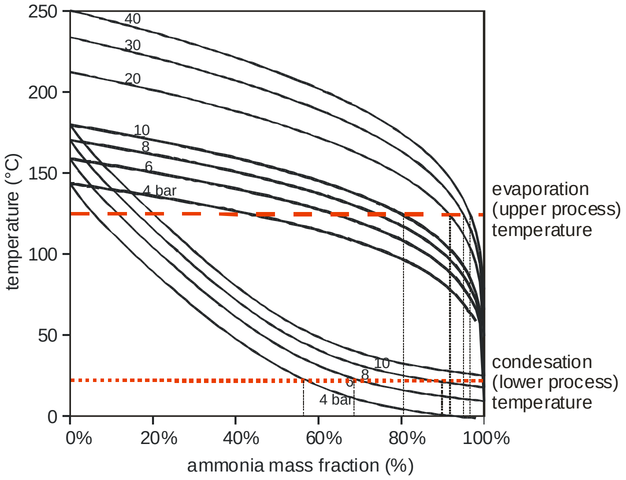


Figure 7: Phase diagram of the ammonia water mixture covering 4 to 40bar (vapor saturation lines) and 4 – 10 bar (liquid saturation lines). The bold broken line and the bold dotted line symbolize the upper and lower temperature in the cycle. The fine vertical lines indicate intersections of vapor saturation line and liquid saturation line with upper and lower temperature, respectively. These intersections mark possible states in the cycle.

other end of the cycle. Besides, the distance of the isobars in figure 7 gives a first idea about the sensitivity of the system. At high ammonia concentration small changes of the concentration cause a steep increase in pressure, the system shows a high sensitivity towards pressure and composition of the mixture. Therefore, modelling requires exact data for the thermodynamic properties as well as information about pressure losses in the equipment. The demands of high ammonia concentration in the working fluid during evaporation and expansion and low ammonia concentration during condensation are nicely fulfilled by the distillation and mixing processes in the Kalina cycle.

5 Conclusions and Outlook

Thermal efficiency alone does not allow proper comparison of geothermal power plants. In an interdisciplinary team overall efficiency is an equally adequate and easy-to-understand method. Both, ORC as well as the Kalina cycle are in a stage of development where simulation tools and numerical modelling sustain the design process. Phase diagrams allow a general understanding of the design rules and optimisation paths especially for the more complex Kalina cycle. Parameter studies showed that only proper dimensioning of the apparatuses and machines and exact tuning of the process parameters guarantee successful optimization. The link between the tools used to calculate the thermodynamic properties of the working fluids properties and the cycles is still missing. Moreover, operational data are needed to substantiate the present results and generate general design guidelines.

Acknowledgements

The work presented in this paper is part of a multidisciplinary project, carried out by research institutes, universities and industrial partners. BMWi, BMBF, BMU, MWI and MWFK (Federal and Brandenburg State Ministries of Economy, of Research and Education, of the Environment) fund the project.

6 References

Bejan, A., Tsatsaronis, G. and Moran, M. (1996). *Thermal Design & Optimization*. John Wiley & Sons, Inc., New York. 542 pp.

Delft University of Technology (2000). *Cycle-Tempo - A program for thermodynamic modeling and optimization of energy conversion systems, Release 4*. Faculty of Mechanical Engineering and Marine Technology, Department of Process and Energy Technology, Delft, Netherlands.

Köhler, S. (2002). Geothermisch angetriebene Kraftwerke - Systembetrachtung und Prozessvergleich. In: *Geothermische Stromerzeugung Stand der Technik und Perspektiven*. Workshop proceedings, Potsdam 17./18. Oktober 2002. VDI Berichte 1703, VDI-GET (Ed.). pp. 71-84.

Maack, R. and Valdimarsson, P. (2002). Operating Experience with Kalina Power Plants. In: *Geothermische Stromerzeugung Stand der Technik und Perspektiven*. Workshop proceedings, Potsdam 17./18. Oktober 2002. VDI Berichte 1703, VDI-GET (Ed.).

NIST Reference Fluid Thermodynamic and Transport Properties – *REFPROP Version 7.0* (2002). U.S. Department of Commerce, Boulder, Colorado.

VDI-Wärmeatlas (2002). Berechnungsblätter für den Wärmeübergang. Springer-Verlag, Berlin.