

Thermodynamic Evaluations for Efficient Energy Conversion of Geothermal Heat

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ABSTRACT

Power generation from geothermal energy in Germany is a rather new sector. Typically, drilling holes are at a depth of ca. 4 km with geothermal water temperature of ca. 150 °C (ca. 420 K). With these boundary conditions an Organic Rankine Cycle (ORC) is used for power generation. This paper describes the numerical calculation of such ORC-cycles by means of the commercial code IPSEpro. With the resulting thermodynamic values for pressure or temperature respectively, an overall efficiency is determined. In addition, the calculations have been carried out for the working fluids isopentane and R-245fa. The thermodynamic fluid properties from IPSEpro have been validated with data from the database Refprop of the National Institute of Standards and Technology (NIST). The deviations of IPSEpro are discussed within this paper.

An alternative application for geothermal energy are hybrid power stations. There the geothermal heat can be used for the preheating of the water steam cycle (WSC) of conventional power stations. This paper compares from a technical point of view the net power output of single power generation from geothermal energy within an ORC respectively an WSC with the combined power generation within a hybrid power station. The calculations show that the increase of efficiency of the WSC is mainly limited by the steam quality at the same boundary conditions. The advantage of preheating the WSC of a big power plant with geothermal energy depends on the ratio of power output of the WSC and the ORC.

1. INTRODUCTION

By definition, geothermal energy is the energy stored in form of heat under the earth's surface. Its potential is inexhaustible on a human timescale, comparable to that of the sun. Typically it is used to produce electricity or for district heating.

The German government and the EU has the target to cover 50% of the whole energy demand by renewable energy by 2050. In electricity sector until 2010 12,5% and 2020 20%. Geothermal energy can supply 50% of the annual energy demand in Germany, Paschen et.al.(2003).

The main advantage compared to the other renewable energies solar and Wind is the baseload character of geothermal energy. The challenge is the efficient production of heat and power at a low temperature level of 100°C to 200°C.

In case of electricity generation from geothermal heat, hot mineral water with ca. 200°C is pumped upward and converted into electric power. In order to produce electricity at such low temperatures the water steam rankine cycle (WSC) is not efficient due to the high vaporization temperature So usually organic rankine cycles (ORC) are used.

Applications of the ORC process extends over a wide temperature range of the heat source. This starts from approximately 100 °C to 200 °C with the geothermal energy, over 300 °C to 450 °C during the waste heat utilization.

Among the particularly interesting application the generation of electricity of waste heat from block heat and power plants the combination of the ORC process with solar thermal plants are also interesting concepts.

Most the ORC plants operated in a capacity range of 200 kW_{el} to 2 MW_{el}. With regard to standard used fluids and circuit concepts an electrical efficiency is reached of approximately 12%.

Modern fossil fuel power stations work by steam pressures of ca. 250 bar and temperatures of up to 650 °C in a Rankine steam cyclic process with efficiencies approx 43%. The feedwater heating with geothermal energy (hybrid power stations) seemed to be a more efficient way to produce electricity than a stand alone ORC power plant.

In order to get power plant concepts with higher efficiencies the usage of a thermodynamic simulation tool is helpful. We use the power plant simulation IPSEpro from Simtech with a beta version of the low temperature library for OR-Cycles. This library include the fluid properties of ispentane, neo pentane, pentane, R245fa, toluene and MDM. The focus lay on isopentane as an reference fluid and R245fa. Both are organic fluids with different crit. temperatures and molweights.As in fig.1 pictured R245fa shows less retrograde behavior compared to isopentane.

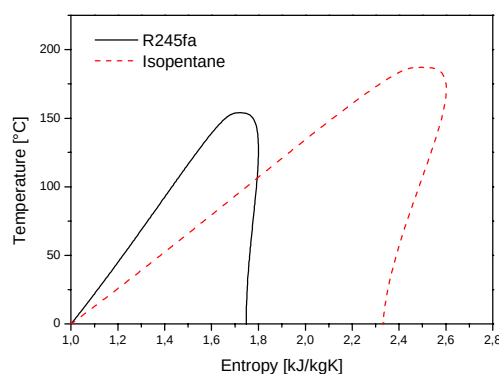


Figure 1: Temperature-Entropy Diagram of isopentane and R245fa.

It is also possible to calculate the overall efficiency for a hybrid power station. One disadvantage is the more restricted selection of plant locations due to the limited distance of heat transfer.

As we will show in this work it is important not to look only on the efficiency of power cycles, because the selection

of working fluid, power plant concepts and power output could be also a important factor in case of electric power generation.

2. VALIDATION OF FLUID PROPERTIES AND SIMULATION

The fluid properties in terms of crit. pressure, crit. temperature, enthalpy, entropy have a strong effect to the simulations results. In order to examine these effects we compare the fluid properties of IPSEpro with the database REFPROP (2007) of the National Institute of Standards and Technology (NIST). The two used fluids are iso-pentane as a reference fluid and R245fa.

Table 2: Fluid properties of isopentane and R245fa.

Name	Structure	Crit. Temperature °C	Crit. Pressure bar	Molw. kg/kmol	
Isopentan	2-Methylbutan <chem>CCCC(C)C</chem>	C ₅ H ₁₂	187,25	33,8	72,15
R245fa	1,1,1,3,3-Pentafluoropropane <chem>CC(F)(F)C(F)(F)F</chem>	C ₃ H ₃ F ₅	154,1	36,4	134,03

2.1 Fluid properties

The following Tables show the characteristic properties of the used fluids and the Reference point data. The latter is important for comparison with other data sources. In case of R245fa the value of enthalpy is near 200 kJ/kg and entropy approx 1 kJ/kgK. This is close to the reference point of the IIR (International Institute of Refrigeration) but at this calculation we used the IPSEpro fit reference data, list in Tab. 3.

Table 3: Reference points of isopentane and R245fa.

Working fluid	Temp. °C	Pressure bar	spec. Enthalpy kJ/kg	spec. Entropy kJ/(kg K)
Isopentan	25	0,01	0	0,53207
R245fa	0	0,01	200,46	1,0016

The relative deviation of the specific enthalpy h between NIST and IPSEpro is calculate with equation (1). The calculation of the entropy deviation accomplished in the same way.

$$\text{Deviation} = \frac{h_{\text{NIST}} - h_{\text{IPSEpro}}}{h_{\text{NIST}}} \cdot 100 \% \quad (1)$$

Figure (1) shows the deviations of enthalpy and Entropy of isopentane and R245fa for different temperatures. The deviations of isopentane decrease with increasing temperature. In contrast to it the deviations of R245fa increase with rising temperature. But overall the deviations do not exceed 1,5% .

So we can conclude that there is a good agreement of the examine fluids properties implemented in IPSEpro compare with the REFPROP database.

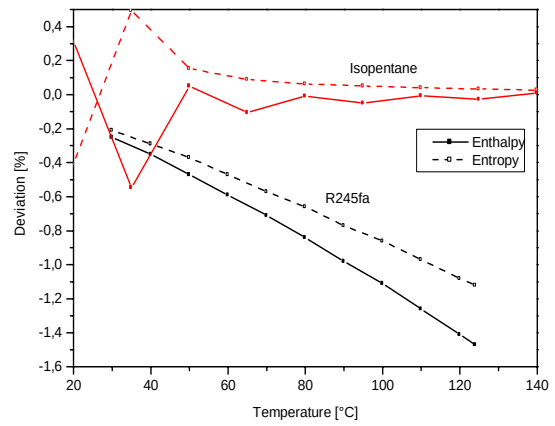


Figure 2: Deviation of Enthalpy and Entropy for isopentane and R245fa.

2.2 Validation of Simulation

In order to validate the simulation tool IPSEpro it is necessary to compare a whole simulation with reference data. For this task we used the data of Köhler (2005) list in table 3. To illustrate the single steps fig 3 shows the cycle process in a temperature-entropy diagram.

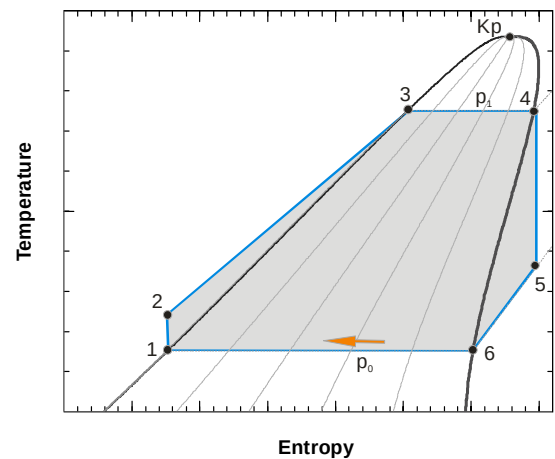


Figure 3: Temperature / Entropy-Diagram of isopentane without losses.

Table 3: Comparison of the simulation results of Cycle Tempo and IPSEpro data.

Process step	Temperature [°C]	pressure [bar]	Enthalpy [kJ/kg]	Entropy [kJ/kgK]
1→2 pump	38,3/38,3	6,30/6,30	336,9/304	1,08/1,08
2 → 3,4	88/88	5,50/5,50	412,6/412,4	1,18/1,17
4→5 Turbine	61,4/61,4	1,50/1,50	36/36,7	0,02/0,03
5→1 condenser	61,6/ 61,6	1,50/1,50	39,7/41	0,12/0,12

This basic case include a constant thermal water temperature of $t_{w,in}=150^{\circ}\text{C}$, reverse temperature of $t_{w,out}=90^{\circ}\text{C}$, massflow $\dot{m}_w= 20 \text{ kg/s}$. This lead to an heatflow of $Q_{th}=5016 \text{ kW}$. The aircooling system has a pressure loss of 1 bar, temperature 15°C (water) and 20°C (air) with a allowance heating of 5 K(water) and 10 K (air).

The results shows a good agreement of the temperature, pressure and entropy only the enthalpy has a difference of 9,8% from step 1 to 2, due to different heat exchanger interconnection at this point. The other deviations are smaller 1%.

2.3 Simplified model

We start the calculation with a theoretical approach due to be able to evaluate the different influences to the power output and efficiency. This model not includes pressure losses and efficiencies of the power cycle units. It supposes a minimum temperature difference of 20K for the heat transfer from thermal water to the ORC fluid. Fig. 4 shows the qualitative ORC-process in a TS-Diagram.

If we look at the heat transfer into the process and balance the energy flows fig.4, than we could describe the total energy transfer with Eq.(2).

$$\dot{Q}_{zu} + \dot{W} = \dot{H}_2 - \dot{H}_1 \quad (2)$$

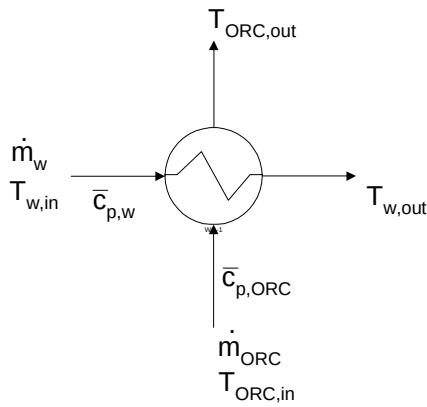


Figure 4: Heat exchange model

$$\dot{m}_{ORC} = \frac{\dot{Q}_{ORC}}{r_{ORC}} = \frac{\dot{Q}_w}{r_{ORC}} = \frac{\dot{m}_w \cdot c_{p,w} \cdot (T_{w,in} - T_e - \Delta T_{min})}{h_4 - h_3} \quad (3)$$

The massflow $\dot{m}_{ORC}$ is calculate by the energy balance of the vaporizer eq. 5 with Q heat flow , r vaporization enthalpy, T_e vaporization temperature and ΔT_{min} as the minimum temperature difference in the heat exchanger.

Thus the mass flow of the ORC medium depends only of the evaporation temperature and the enthalpies in the ORC cycle, resulting from it. For this reason the mass flow is manual determined for each evaporation temperature in the ORC cycle and used in the simulation as constant value. The return temperature of thermal water is calculated by :

$$T_{w,out} = (T_e + \Delta T_{min}) - c_{pm} \frac{T_e - T_{con}}{r_{ORC}} (T_{w,in} - T_e - \Delta T_{min}) \quad (4)$$

With T_e =vaporization temperature, $T_{w, in}$ = thermal water temperature, T_{con} = condenser temperature.

The turbine power output $\dot{W}$ of the ORC result in eq.5 (according to Bejan (1996)).

$$\dot{W} = \eta_{is} \cdot \eta_{mech} \cdot \dot{m} \cdot c_{pm} \cdot \left(1 - \frac{T_{con}}{T_e}\right) \cdot (T_{w,in} - T_{w,out}) \quad (5)$$

If we set $\dot{m}$ equal to the mass flow of ORC fluid $\dot{m}_{ORC}$ and c_{pm} the arithmetic middle of the heat capacity of ORC fluid, T_{con} as condenser temperature. $T_{w,in}$ and $T_{w,out}$ as upper and lower thermal water temperature. The efficiency η_{is} is 0,75 and η_{mech} set to unity.

The figure 5 point out the dependency of $\dot{W}$ in relation to the return flow temperature of thermal water $T_{w,out}$. It is obvious that the calculation with a grater temperature range 175/30 and 150/10 results in higher power output than the reference calculation 150/30 but also it could show that the maximum power output move to lower water temperatures $T_{w,out}$ with lower process temperatures $T_{cooling}$.

Lowering the condensation temperature illustrates the seasonal fluctuations of a year. In winter the environment is to be regarded as infinite heat sink with temperature under 5°C . Thus a condensation temperature of 10°C is quite realistic. A detailed view of the effect of the seasonal fluctuations on the electricity yield under the assumption of combined heat and power production apart from the poor electricity generation could be achieved from the Kongressband Geothermischer Vereinigung (2008).

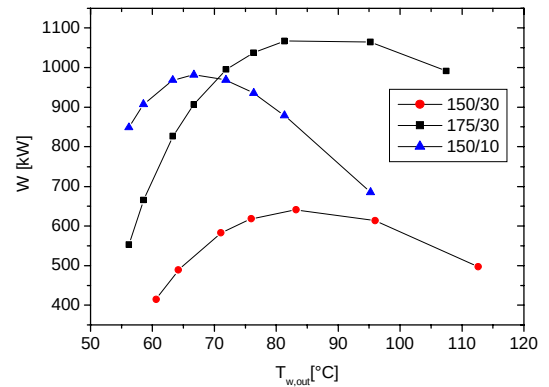


Figure 5: Turbine power output with simplified model, isopentane and at different upper and lower process temperatures $T_{w,in}/T_{con}$.

We calculate also the power output of R245fa and could see that there are only minor deviations caused by the similar physical properties e.g. vapour pressure. The main difference is the nearly doubled mass flow of R245fa. For a mass flow $\dot{m}_{ORC}=0$ the maximum efficiency is reached but no power will be produced.

The curves of the power output are functions of the water return temperature, so that the maximum power can be assigned to a certain point of temperature. This point of temperature corresponds to a certain evaporation temperature of the ORC-fluid. For the range of the combined use of heat and power follows a smaller power output generation, but the supply of warm water with the desired water return temperature is possible without effort. So regarded to the low temperature range up to the maximum power output point (fig.5) offers neither less efficiency nor warm water for heating. From this follows

that a design of a power station in range left of the power maximum on the fig.5 have to avoid. This calculation produces unrealistic high efficiencies η due to the assumption of no losses. Hence, the curves in fig.5 have more a quality character and give an impression of the physical limits. In order to get more realistic values it is necessary to use a numerical simulation tool and to define losses for the calculation.

$$\eta = \frac{P_{\text{gen}} - P_{\text{eig}}}{Q_{\text{zu}}} \cdot 100\% \quad (6)$$

In eq. 6 the P_{gen} is the generator power output and P_{eig} as the auxillary power of the power plant without the thermal water pump and Q_{zu} contain the heat input from thermal water into the ORC .

3. SIMULATION

The IPSEpro delivers different units to build up a simulation flow sheet fig.6 . This figure shows the two types of heat exchanger, the turbine, condenser and the cycle-pump. It has to be mention that the thermal water pump and the air cooling system is not include. The program solve the energy and mass balance and print out the power output, efficiency, enthalpy of the ORC.

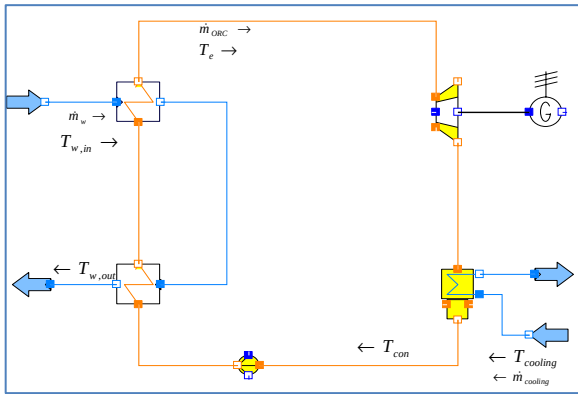


Figure 6: Flowsheet model of IPSEpro. The values mention above specified by user.

In fig.7 three different cases of $T_{w,in} / T_{con}$ are calculated. The efficiency decrease with rising mass flow m_{ORC} . For the case 150/30 we reach the lowest efficiencies while the case 150/10 with a decrease condenser temperature as a winter operation and the case 175/30 with an increased thermal water temperature deliver nearly similar efficiencies. So the increase of thermal water temperature and the decrease of condenser temperature increase the efficiency with respect to the carnot efficiency eq 7.

$$\eta_c = 1 - \frac{T_{con}}{T_{w,in}} \quad (7)$$

The increase of the evaporation temperature in the ORC cycle leads to the fact that the energy which can be supplied by the thermal water will be decrease and so less energy transfer results. The outcome of this trend is that the turbine power output exhibits to a maximum, see fig. 8, fig. 9.

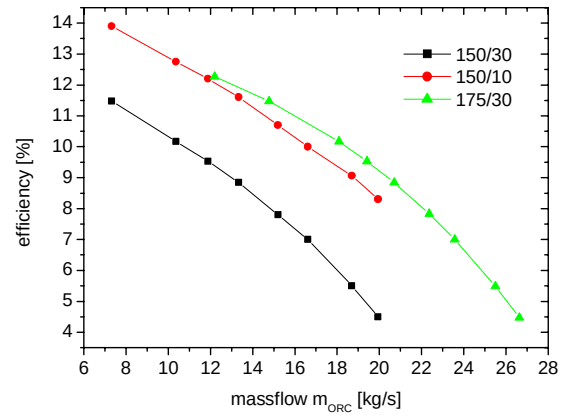


Figure 7: Isopentane gross efficiency for different upper and lower process temperatures $T_{w,in}/T_{con}$.

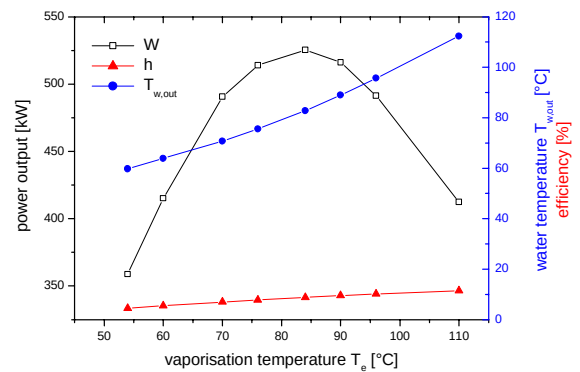


Figure 8: Power output W, water temperature $T_{w,out}$ and efficiency h of isopentane simulation.

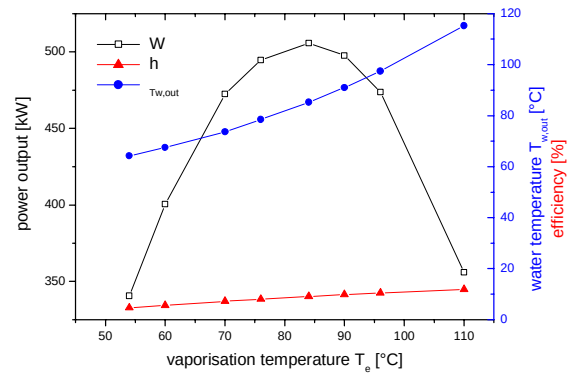


Figure 9: Power output W, water temperature $T_{w,out}$ and efficiency h of R245fa simulation.

The efficiency of the cycle system increases with the rising evaporation temperature. Hence, generally the efficiencies regards mainly to the process temperatures, here is no efficiency difference of both fluids.

Also with R245fa the simulated power output is lower than the theoretically calculated efficiency, caused by the losses of all components of the plant that are considered here. The maximum mechanical achievement of both fluids differs a little bit with 525 KW for isopentane and 506 KW with R245fa. The exact view of the operating pressures of both media shows that isopentane with an operating pressure of 5,8 bar is energetically better, than R245fa with an

necessary operating pressure of 7 bar. Also the view of the cycle mass flows, fig.10 makes clear that with a constant efficiency of 8,9% the R245fa fluid result in a mass flow of 18,7 kg/s compared to 13,3 kg/s by isopentane. In the point of the maximum turbine power the two working fluids have mass flows of 18,7 kg/s (R245fa) and 13,3kg/s (isopentane).

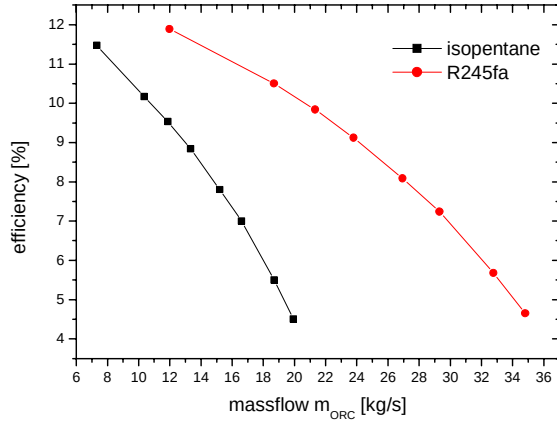


Figure 10: Efficiency for isopentane and R245fa as a function of massflow.

Certainly higher mass flows and higher pressures lead to less efficiency and higher wear. A further argument for the employment from isopentane is that the power output is not so strong related to the condensation temperatures as R245fa. Thus also in the summer with increased ambient and condensation temperature, power plant operation is profitable.

3.2. Hybrid power plant

3.2.1 Simulation of reference ORC power plant

To evaluate the effect of preheating of feedwater in a steam power plant with geothermal heat the following condition are defined.

Heat input by thermal water $Q_g=5$ MW without losses. The thermal water temperature is specified to be 150°C. The isentropic efficiency of the ORC turbine is set to 0,75, pump efficiency 0,84, subcooling temperature in condenser 2K, condenser input temperature of 15°C, heat exchanger pressure loss 0,2 MPa and heat loss of 1%, generator efficiency of 0,98%.

The numerical calculation deliver the related results of ORC plant with isopentane :

- Electrical power output 577 kW (efficiency 11,55%)
- Electrical net power output 468,5 kW

These parameter are the reference case with which we will compare the ORC with the hybrid power plant.

3.2.2 Simulation of hybrid power plant

Three different power classes of steam plants are calculated. In order to simplify the calculation the steam cycle has no feed water preheating (except the geothermal heat) and no reheating that are usually used in this power range. So the efficiency is not as high as possible, but to examine the basic dependencies from geothermal preheating it is sufficient.

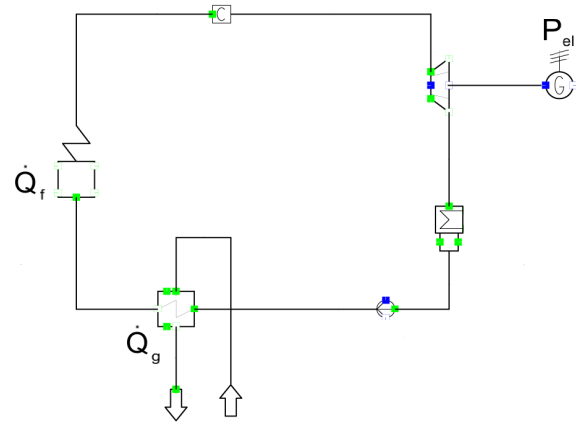


Figure 11: Power plant flow sheet in IPSEpro with geothermal preheating.

Fig.11 shows the plant flow sheet in IPSEpro with Q_f as the boiler heat input, generator power output P_{el} and the geothermal heat exchanger with Q_g .

Table 4 : Result of hybrid plant simulation

Power class	100 MW	100 MW	1000MW
Steam parameter	4,1 MPa/440°C	25 MPa /560°C	25 MPa /560°C
Boiler output MW	340	280	2800
Efficiency %	29,42	35,64	35,64
Electrical power kW	100027	99794	997937
El. power with geothermal perh. kW	101663	101774	999917
Difference kW	1636	1980	1980

The results of the hybrid plant simulation shows that the geothermal heat input is coupled to the higher efficiency of the steam cycle. In case of the lower power output class (100MW) with realistic steam parameter of 4,1MPa and 440°C the calculation of electric yield result to 1636 kW. With theoretically improved steam parameter of 25 MPa and 560°C the electric yield calculation return with the same value of 1980 kW as for a power output ten times higher. If we compare the increase of the steam cycle power output with the stand alone ORC, for the same thermal heat input, we find a 3,4 higher power output for the hybrid plant. Also the efficiency in the first case (100 MW) increase by 0,048 % point. With increasing power output the difference in efficiency runs against zero.

It has to taken into account that these result based on calculations without regard to the thermal water pump. The energy is need for feeding thermal water could exceed 1/3 of the electric power output. Due to other uncertainties like pollution it could be expected that real applications have much lower electrical power output depending on boundary conditions. Additional simulation and experimental data are necessary to improve the power plant design.

4. CONCLUSION

Due to the geological conditions in Germany, thermal water temperatures up to 200°C are to be expected. For this reason the development of a more efficient power station with secondary cycle is needed. In such power stations the heat of thermal water transferred to a secondary fluid - usually at low temperatures vaporize organic fluids. The operation of the power station is similarly as with water-operated power stations. The working fluid is heat up to an evaporation temperature and relaxed in a turbine. Due to the

high temperatures at the turbine outlet a combined heat and power production is advisable.

In this work the concept of electricity generation take priority. The energetic concept for the operation of the power station contains the selection of the medium. It is energetically favorable to arrange the process in such a way to the critical temperature of the medium that it is a little higher than the upper process temperature. Thus only few fluids come into the closer selection for each source temperature. The thermal water parameters are determining for the design of a power station. Two fluids were examined, whose critical temperature and steam pressure lay in the desired range.

First a theoretical calculation of the process parameters, for isopentane and 1,1,1,3,3-Penta-fluoro-propane(R245fa), accomplished for in each case three combinations of thermal water input and condensation temperature. A goal of this work was it to illustrate different low-temperature processes and to compare the power output yields with one another. For the evaluation of a process the parameter power output, efficiency and detection of the point of the maximum power output. Also the process parameters evaporation temperature and evaporation pressure, steam quality, superheating and the condensation temperature are important for the optimization.

In this work we solve the energy balance of an ORC with the simulation tool IPSEpro in order to compare the power output and efficiency of the two working fluids isopentane and R245fa. At first we validate the fluid properties include in IPSEpro and find a good agreement with the reference database REFPROP. Also the comparison of the calculation results with Köhler 2005 delivers the same results.

The simulated processes show the development of the power output and the efficiency with rising evaporation temperature of the media. While the power output exhibits a maximum, the efficiency rises with rising evaporation temperature. At the maximum power output the isopentane

deliver 20kW or 4% more power in the simulation than R245fa in case 150°C/30°C.

As a further aspect the work examine the combination of a steam power plant with geothermal preheat (hybrid plant). With a simplified model plant it could be shown that the usage of geothermal energy in hybrid plant lead to higher efficiencies and up to 3,4 times higher power output.

REFERENCES

- Baehr H.D: Thermodynamische Grundlagen und technische Anwendungen, Springer Verlag 13. Aufl., Berlin 2009
- Bejan, A., 1996: 'Models of power plants that generate minimum entropy while operating at maximum power.' Am. J. Phys., v. 64, p. 1054 - 1059.
- Kongressband Geothermischer Vereinigung: Geothermische Vereinigung, Kongressband des Geothermiekongresses. 11.-13. November 2008, Karlsruhe
- Herbst G: Simulation eines Niedertemperaturkreisprozesses zur Stromerzeugung mit IPSEpro, Diplom thesis, Hochschule Karlsruhe 2009
- Huenges, E., 2001: Strom aus Erdwärme in Deutschland, FVS Themen 2001
- IPSEpro: homepage www.simtechnology.com
- Köhler S: Geothermisch angetriebene Dampfprozesse Analyse und Prozessvergleich binärer Kraftwerke, Phd-thesis, TU Berlin 2005
- NIST : Standard Reference Programm REFPROP, U.S. Department of Commerce Technology Administration, Vers.8.0,2007
- Paschen H., Oertel D., Grünwald R. : Möglichkeiten geothermischer Stromerzeugung in Deutschland, Das Büro für Technikfolgenabschätzung beim Deutschen Bundestag (TAB) 2008