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Performance Optimization of ORC Power Plants

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ABSTRACT

This paper presents the development of correlations for performance optimization of ORC power plants. The current work addresses a brine temperature range from 100°C to 300°C and ambient temperatures from 10°C to 35°C. The selected working fluid and the predominant conditions in the power plant cycle have a great influence on the cycle performance and consequently on the design of the power plant and its net power output. Basic studies on economic and technical issues create needs for models of the expected power output of a geothermal power plant. For this purpose GESI – an in-house thermodynamic MATLAB code – has been developed. GESI calculates optimal live vapour parameters under given boundary conditions. In order to accelerate the pre-calculation process, correlations between net power output and brine and ambient temperature, respectively are developed.

1. INTRODUCTION

Since the last years, new concepts for electricity generation using low-enthalpy / low-temperature sources are under investigation to reduce the electricity generating costs and to satisfy the rising energy demand within a decentralized electricity production approach. At low temperatures (usually below 300°C) conventional steam plants with a Clausius-Rankine Cycle are not feasible. As alternative, Organic Rankine Cycles (ORC) are applicable to such low temperatures and are state of the art. Thereby, refrigerants or hydrocarbon based working fluids are used instead of water. Applications of ORC's are mainly geothermal power production from low enthalpy sites.

In Germany the number of these power plants is continuously rising: In 2005 the installed geothermal capacity was only about 0.2 MW, which is equivalent to an amount of 1.5 GWh/year of produced energy. Until 2010 these numbers climbed up to 7.1 MW of installed capacity and 50 GWh/year of produced energy. Comparing these numbers the increase in capacity amounts to 7 MW, which is equivalent to 2987 %, and the increase in produced energy is 49 GWh/year, which corresponds to 3249 % in five years. A forecast for the installed capacity in 2015 was about 15 MW (Bertani (2012)). Until 2013 there were eight geothermal power plants installed, producing 3.31 MW of electricity. Four plants are under construction right now (effective April 2014, source: www.geothermie.de (2014)) with a total of over 26.6 MW in electricity production and 14 planned (estimated electricity production of 76 MW). So the estimation of Bertani (2012) will hopefully be not only met, but surpassed. Furthermore, the utilization of waste heat from energy intense processes comes into the focus of this technology. Here electricity production is a by-product with rising economic aspects. Manufacturer of internal combustion engines for decentralized heat and power production from CNG (compressed natural gas) or Diesel address the ORC technology to increase the rate of electricity production by coupling their exhaust heat exchanger with an ORC.

One part of Germany's renewable energy portfolio is the improved utilization of geothermal energy. Designing geothermal power plants suitable for low-enthalpy regions as there are available in Germany hits these targets. According to Franco and Villani (2009) binary power plants are the best energy conversion systems to exploit low-temperature water-dominated geothermal systems. In consequence, this technique, like Kalina or Organic Rankine Cycle, is used to produce electricity from low-enthalpy geothermal sites. In a heat exchanger the heat of the pressurized geothermal fluid is transferred to a secondary working fluid. Different boundary conditions, defined by the geothermal site, influence the selection of the working fluid. Furthermore, geothermal power has to be generated efficiently due to high drilling costs respectively high investments for the geothermal power plant in the context of the available (only) low-enthalpy potential in Germany. Geothermal drilling in general is expensive for three main reasons: First of all, the technical challenge, which means that special tools and techniques are required here. Then the diameter of the hole and casing has to be large, since the produced fluid is of low value and thus large flow rates are needed. And last, geothermal wells, even in the same geothermal field, are unique and therefore the learning curve from experience is less useful, than for instance in oil and gas drilling (after Finger and Blankenship (2010)). At every stage of a geothermal project, project developers have to assess the financial risks and the economic potential of the ongoing project.

The predominant conditions in the loop and the choice of the fluid have significant influence on the cycle performance and consequently on the design of the power plant and its net power output. The net power output of the power plant directly correlates with the temperature of the brine but also depends on the selection of a suitable working fluid. On the basis of measurements of the brine temperature and estimations of the required mass flow rate the economic feasibility of a geothermal power plant at an early time is essential.

Currently, the simulations of power plant processes are very accurate, but there is a large number of working fluids and variables that have to be considered. This multiplicity yields very time-consuming numerical optimizations. A first decision on suitable working fluids can be made depending on the brine temperature. Different investigations on ORC performance in the field of geothermal and working fluids were conducted in the last years. Al-Weshahi et al. (2014) studied a brine temperature of 60-200°C and 25 working fluids, Chen et al. (2010) were looking into 35 fluids and low-grade heat, which is not specified further. Astolfi et al. (2014) were addressing a brine temperature of 120-180°C and 54 potential working fluids, whereas Le et al. (2014) were limiting the geothermal parameters to 150°C and the working fluids to 8, including zeotropic mixtures. In this study, brine temperatures between 100°C and 300°C are addressed, along with ambient temperatures between 10°C and 35°C, which correspond with European conditions. To reduce the calculation time and to investigate all possible working fluids, GESI – an in-house thermodynamic code, using fluid properties taken from the NIST database (Lemmon et al. (2013)) – has been developed and applied. GESI allows the simulation of optimal live vapour parameters under given boundary conditions as well as the systematic analysis of typical organic fluids. To accelerate the pre-calculation process, correlations between net power output and brine, ambient and condensation temperature were developed within the current study. The developed correlations allow fast and reliable predictions of net power output at given temperatures at the hot and cold end of an ORC system.

The design and maintenance of binary geothermal power plants is an expensive venture. Hence, it is necessary to make sure that the results of design and analysis software are characterized by a high degree of accuracy and reliability. To ensure this, the programs must be subjected to a comprehensive validation process. With the help of experimental data, predictability can be determined in the context of pre- and post-test analyses.

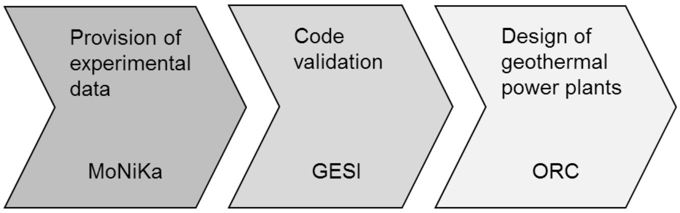

Figure 1: Flow chart for the design and evaluation of ORC power plants

With the commissioning of MoNiKa, a small-scale experimental geothermal loop adapted to low temperatures, experimental data will be provided to validate the geothermal simulation code GESI. The results will be the input for an optimized design of new geothermal power plants and for the optimization of already operating ORC power plants.

This paper will briefly describe the working principle of an Organic Rankine Cycle along with its advantages regarding electricity production from geothermal heat sources. Furthermore, the in-house program GESI, which is used for parameter variation, and its features are introduced. The simulation with GESI corresponds to a comprehensive variation of important cycle parameters ($T_{th,in}$, $T_{th,out}$, $T_{amb,in}$, $T_{amb,out}$, $\dot{m}_{ORC}$, p_{ORC}, T_{ORC}). Obtained results are discussed and a summary is given. Finally, MoNiKa, the experimental setup to validate numerical simulations within a small scale binary power plant is presented. The construction of the modular power plant is currently ongoing and the design point of the power plant is presented.

2. ORGANIC RANKINE CYCLE (ORC)

Conventional steam driven power plants follow the Clausius Rankine Cycle. This process uses water as working fluid and is state-of-the-art in nuclear or coal fired power plants. In order to use water as working fluid a sufficiently high heat supply has to be ensured, because of the high evaporation temperature of water at elevated pressure. With respect to electricity production from low to medium enthalpy reservoirs, it is useful to consider other working fluids with lower evaporation points. In case of an organic working fluid, the process is called Organic Rankine Cycle. As an example, Figure 2 shows a geothermal production well as a heat source. In general, the heat source and sink in ORC processes vary in layout depending on the application (geological conditions, environment, application, etc.).

The geothermal water is pumped from the production well into a heat exchanger, in Figure 2, divided into a superheater and a preheater. The geothermal water which has been cooled down in the heat exchanger is pumped back underground by leading it into the injection well. On the secondary side, the feeding pump transports the cold working fluid into the pre- and superheater. In the preheater, the fluid is heated till the saturation temperature and is fully evaporated. In the superheater the dry vapour is superheated. This superheated vapour is directed to the steam turbine where the energy is transferred into mechanical work. The expanded fluid is condensed eventually in the condenser before the whole process starts over again. In most cases, an air-heat exchanger is used for the condensation of the organic fluid. An illustration of the *T-s*-diagram of an ORC using isopentane as working fluid, which is regularly used in geothermal power plants, is given in Figure 3.

One way to increase the net power output of future ORC power plants is to focus on the energy losses and their reduction. A simple concept coming from coal fired power plants of the 60’s is to increase the pressure to the supercritical state. The exergy losses during heat transfer correspond to the region between the boiling curve of the working fluid and the temperature gradient of the brine in the *T-s*-diagram. For subcritical cycles the bend of the boiling curve leads to a dominant increase of the exergy losses during evaporation. At elevated pressures above the critical pressure the boiling curve of the working fluid leads to a slight S-shape and a significant lower temperature difference between brine and working fluid.

The fluid determines the location of the critical point (CP) in the *T-s*-diagram. The process is either sub- (black line, Figure 3) or supercritical (dotted line, Figure 3) depending on the pressure at which the heat is supplied. In the subcritical case the fluid evaporates as it passes through the two-phase region.

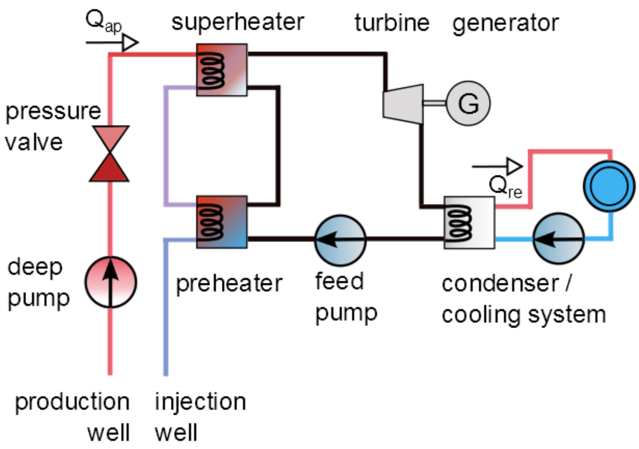

Figure 2: Schematic design of an ORC in geothermal application with main components

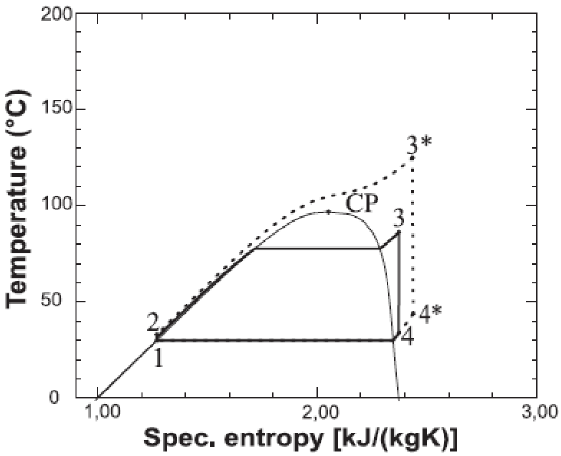

Figure 3: Sub- and supercritical ORC in a T-s-diagram. The changes of state of an ideal ORC process are the following: 1-2: isentropic compression, supply of work to the cycle; 2-3: isobaric heat supply; 3-4: isentropic expansion, extraction of work from the cycle; 4-1: isobaric condensation.

In general, the heat (Q_{ap}), which is applied to the process, is calculated from the enthalpy difference $h_3 - h_2$ between outlet and inlet of the heat exchanger and the cycle mass flow rate $\dot{m}_{\text{ORC}}$ and is defined as follows:

Applied heat:

$$Q_{\text{ap}} = \dot{m}_{\text{ORC}} \cdot [h_3 - h_2] = \dot{m}_{\text{cool}} \cdot [h_{\text{out}} - h_{in}] \qquad (1)$$

The indices correspond to process states as shown in Fig. 2. Heat losses to the environment can be neglected under the assumption of an ideally isolated heat exchanger. Then, the applied heat is identical with the heat removed from the source. For removing the heat applies, by analogy:

Removed heat:

$$Q_{\text{re}} = \dot{m}_{\text{ORC}} \cdot [h_4 - h_1] = \dot{m}_{\text{Th}} \cdot [h_{\text{in}} - h_{\text{out}}] \qquad (2)$$

In contrast to water, many organic fluids show a positive slope of the dew line in the *T-s*-diagram. They are called retrograde and are not part of this study. Working fluids with a negative slope of the dew line in the *T-s*-diagram enable expansion to condensation temperature. In this case, the maximum admissible void fraction at expansion into the two phase region has to be met, because otherwise damage of turbine plates by drop impact could occur.

The above mentioned ideal changes of state of the working fluid are not obtained in reality. In the heat exchanger and the condenser pressure losses cannot be avoided. Friction and turbulences cause an increase in entropy in the pump and the turbine, so no isentropic change of state is possible. This deviation from the ideal case is usually defined in the stationary process calculation via the isentropic efficiency of pump η_{pump} and turbine η_{turb}:

$$\eta_{turb} = \frac{h_3 - h_4}{h_3 - h_{4\text{is}}} \qquad (3)$$

$$\eta_{pump} = \frac{h_{2\text{is}} - h_1}{h_2 - h_1} \qquad (4)$$

The index is stands for the isentropic change of state. The work applied in the pump P_{pump} is calculated from:

$$P_{\text{pump}} = \dot{m}_{\text{ORC}} \cdot (h_2 - h_1) \qquad (5)$$

The work applied in the turbine P_{turb} is calculated in analogy:

$$P_{\text{turb}} = \dot{m}_{\text{ORC}} \cdot (h_3 - h_4) \qquad (6)$$

The net power output (P_{net}) of these processes is calculated from the turbine efficiency minus the pump efficiency and minus the auxiliary power of other power plant components (further pumps, heaters, valves, etc.) that is usually neglected in the stationary dimensioning. This study concentrates on P_{net}, because it is the relevant quantity to evaluate the quality of the thermodynamic loop. In geothermal engineering, the heat as such is costless; only the investment for the power plant is included in economic considerations. Therefore, the efficiency of the power plant is not in the direct focus.

In low to medium enthalpy reservoirs an ORC with a suitable working fluid can be used to produce electricity efficiently. In addition, an ORC can be used as bottoming cycle in geothermal application. In a flash process the geothermal water is used directly. It is partly expanded and separators are used to separate vapour from liquid. The vapour is used to drive a turbine, while the remaining heat of the liquid phase can be used in an ORC. With this concept the efficiency of the power plant in total can be increased as Moya and DiPippo (2007) have shown. They describe the installation of such a bottoming cycle in Costa Rica, where the liquid phase after separation has a temperature of 165°C. They assert an increase in total efficiency of 13%.

Besides the use of geothermal heat sources other heat sources might be applied. In multiple chemical and process engineering plants a large part of the applied heat is dissipated to the environment. In order to enhance the efficiency of those processes and to diminish the environmental impact of emissions, it is reasonable to make this waste heat usable. In temperature ranges up to 650°C ORC processes can be applied for electricity production and result in savings for the operator and an enhanced total efficiency of the process, without affecting it, as Bundela and Chawla (2010) pointed out. Here, the capabilities are versatile. Besides the waste heat utilization of thermal power plants, particularly the field of manufacturing engineering, e.g. cement production, offers a large potential.

3. GESI

GESI (Vetter (2011)) is short for GEothermal SImulation, which is under development at the KIT/IKET. It is used to model and simulate ORC and Kalina power plant processes with a geothermal heat source. With GESI thermodynamic processes are optimized according to the selected fluid and the considered vapour parameters like temperature and pressure. The thermodynamic data of all included working fluids are taken from REFPROP 8.0 of the National Institute of Standards and Technology (Lemmon et al. (2013)).

The sub-programs concerning ORC were used to obtain the results discussed in this paper. First of all, the parameters pressure, temperature, density, enthalpy, entropy and vapour quality of the different states of the selected fluid and the process characteristics (mass flow rate, performance, transferred heat, efficiency) are calculated. Then the cycle is shown in a *T*-*s*-diagram. The critical temperature, the critical pressure and the two-phase region corresponding to the selected fluid are displayed as well.

In the first input mask the necessary data consists of the temperature prior to the feed pump (saturated fluid), the isentropic efficiency of turbine and pump and the properties of the vapour. To define these parameters, pressure and temperature of the live vapour are specified. Additionally, the heat exchanger has to be characterized. Therefore, the inlet temperature and pressure of the thermal water has to be given, as well as its mass flow rate and the minimal temperature difference (MTD) and the pressure loss in the heat exchanger. The last thing to be characterized is the condenser, which is done by choosing either water or air cooling. In the case of water cooling, the cooling water inlet temperature is needed along with the water pressure, the MTD and the pressure loss in the condenser. In case of air cooling a constant pressure loss is assumed to calculate the fan performance from the cooling air mass flow. GESI only gives the temperature of the air and the mass flow, the other input parameters are the same as with water cooling.

The void fraction in the two-phase region after the turbine, the efficiency of the heat exchanger and the condenser (mass flow rate of coolant and outlet temperature) are calculated with a bisection method, an iterative pattern, which is described exemplary for the efficiency of the heat exchanger in Figure 4. At first, the thermal water outlet temperature is set depending on the MDT in the heat exchanger and the inlet temperature of the working fluid. With this input the temperature trends of the thermal water and working fluid in the heat exchanger are calculated. Once the temperature difference is smaller than the MDT, the outlet temperature will be raised. This iteration is carried out until the MDT is met. To increase the calculation speed, the first iteration has an increment of 10°C for raising the temperature, the second will use 5°C, the third 2.5°C, the forth 0.5°C and the last one will use 0.1°C. This principle is used for the efficiency of heat exchanger as well as for the other above mentioned parts.

For the calculation with GESI the necessary input parameters are given in Table 1. The mass flow of the thermal water was fixed to 1 kg/s in order to get a new index number to be able to objectively compare different working fluids. This index number is the specific net power output that can be achieved with a geothermal water mass flow rate of 1kg/s under given conditions. A pressure of 5 MPa is selected, so that the water remains liquid.

The range of the thermal water inlet temperature from 100°C to 300°C represents typical values for binary cycles. The parameters for the ORC process contain realistic values for relevant power plant sizes. The minimal temperature difference in the heat exchanger at the pinch point, which is the minimal temperature difference between brine and working fluid, is assumed to be 5 K.

The program calculates the following cycle data, which are the integral quantities that thermodynamically describe the system. They are used to classify and compare different cycle components, working fluids or boundary conditions.

Net power output:

$$P_{\mathrm{net}} = \dot{m}_{\mathrm{ORC}} \cdot [h_3 - h_4 - (h_2 - h_1)] \tag{7}$$

Gross power output:

$$P_{\mathrm{gross}} = \dot{m}_{\mathrm{ORC}} \cdot [h_3 - h_4] \tag{8}$$

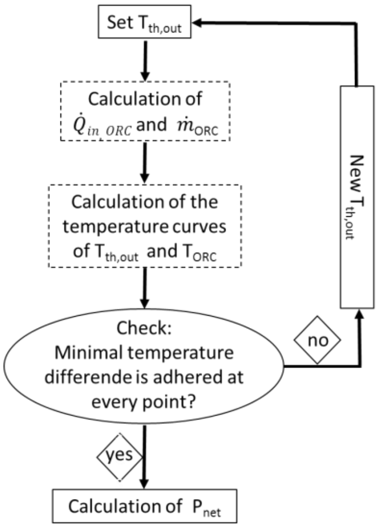

Figure 4: Iterative pattern for the heat exchanger (C. Vetter (2011))

Table 1: Input parameters for calculation with GESI

Thermal water	
Mass flow rate	1 kg/s
Pressure	5 MPa
Inlet temperature	100 - 300°C
ORC process	
Min. void fraction after turbine	0.9
Pump efficiency	0.7
Turbine efficiency	0.8
MTD heat exchanger	5 K
Pressure loss heat exchanger	0.02 MPa
MTD condenser	5 K
Pressure loss condenser	0.02 MPa
Condenser temperature	30°C
Inlet temperature cooling water	19°C
Pressure cooling water	0.3 MPa

Actual efficiency:

$$\eta_{\text{act}} = \frac{h_3 - h_4 - [h_2 - h_1]}{h_3 - h_2} \tag{9}$$

Ideal efficiency:

$$\eta_{\text{ideal}} = \frac{h_3 - h_{\text{is.exp.}} - [h_{\text{is.compr.}} - h_1]}{h_3 - h_2} \tag{10}$$

Applied heat:

$$Q_{\text{ap}} = \dot{m}_{\text{ ORC}} \cdot [h_4 - h_1] = \dot{m}_{\text{ cool}} \cdot [h_{\text{out}} - h_{in}] \tag{11}$$

Removed heat:

$$Q_{\text{re}} = \dot{m}_{\text{ ORC}} \cdot [h_3 - h_2] = \dot{m}_{\text{ Th}} \cdot [h_{\text{in}} - h_{\text{out}}] \tag{12}$$

With this output a variation of live vapour parameters, such as temperature and pressure, is performed in another sub-program. The required input in this case consists of temperature prior to compression, thermal water inlet temperature, its pressure and mass flow rate, temperature difference and pressure loss in the heat exchanger and condenser, isentropic efficiency of turbine and pump. As before the choice is between air and water cooling. And with water cooling the inlet temperature and pressure of the coolant are needed. The output of this routine contains the thermal efficiency, net and gross power output, applied heat in the heat exchanger, outlet temperature of the thermal water and the mass flow rate as functions of the live vapour parameters.

4. SIMULATION WITH GESI

With this output a variation of live vapour parameters, such as temperature and pressure, is performed in another sub-program. At first pre-selected fluids from the NIST data base (Lemmon et al. (2013)) were tested for their suitability as working fluid in a geothermal power plant with the given boundary conditions by GESI. The first attempts in this field of study led to the conclusion, that supercritical processes have a higher maximum net power output than subcritical (Vetter et al. (2013)). Based on those results, this study focusses on the best performing fluids, mostly supercritical, and their behaviour in the thermal water temperature range between 100°C and 300°C. The working fluids and their critical pressures and temperatures are listed in Table 2, together with water and CO_2 for comparison.

Those fluids are analyzed in GESI with respect to their maximum net power output P_{net} depending on the thermal water inlet temperature $T_{th,in}$ at a fixed condensation temperature T_{cond} of 30°C. The output of this analysis is shown in Figure 5. This figure shows that for every $T_{th,in}$ there is one working fluid performing better than the others. At some temperatures the net output of different fluids only differs by some parts of a kW, but especially at higher temperatures the intervals increase. As an example, at 240°C, the difference between P_{net} of R123 (green broken line) and R11 (purple dotted line) is around 14 kW, which is 10% of the maximum achievable P_{net} =144 kW at that temperature.

Table 2: Analysed fluids with critical temperature and pressure

Fluid	Formula	Tcrit [°C]	pcrit [MPa]
R11	CCl3F	197.96	4.408
R114	C2F4Cl2	145.68	3.257
R115	C2F5Cl	79.95	3.129
R123	C2HF3Cl2	183.68	3.662
R125	C2HF5	66.02	3.618
R141b	C2H3FCl2	204.35	4.212
R218	C3F8	71.87	2.640
R227ea	C3HF7	101.75	2.925
R236ea	C3H2F6	139.29	3.502
R236fa	C3H2F6	124.92	3.200
R245ca	C3H3F5	174.42	3.925
R245fa	C3H3F5	154.01	3.651
R290 (Propane)	C3H8	96.74	4.250
R718 (Water)	H2O	373.95	22.064
R744 (Carbon dioxide)	CO2	30.98	7.377
Acetone	C3H6O	234.95	4.700
Perfluoropentane	C5F12	154.01	3.651

As the performance of the selected working fluids differs only slightly, the uncertainties of the fluids have to be taken into account. These errors range between 0.1% and 5% (taken from Lemmon et al (2013)) or are not known. In the case of not specified errors, the error bar for the corresponding fluid was set to 5% (see Figure 6). The error bars are only shown in Figure 6 for reasons of clarity.

In order to get correlations between P_{net} and $T_{th,in}$, the further investigation concentrates on the three best performing working fluids for every $T_{th,in}$. That means for every value of $T_{th,in}$ the three best performing working fluids are selected. Then one curve displaying the best performing fluids is plotted and one for the second best and one for the third. So that in Figure 6 three curves with error bars and trends are obtained. The three best performing fluids were chosen because if errors are taken into account the fluids mostly do not differ significantly. The error bars are larger than the gap between the curves.

After having analysed the above-mentioned potential working fluids (see Table 2), correlations are obtained for the best performing fluid, the second and third at every thermal water inlet temperature. The results are the following:

$$P_{\text{net}} = 2 \cdot 10^{-4} \cdot {T_{\text{th,in}}}^{2,48} ;\ R^2 = 0{,}9967 \quad (13)$$

$$P_{\text{net}} = 2 \cdot 10^{-4} \cdot {T_{\text{th,in}}}^{2,50} ;\ R^2 = 0{,}9973 \quad (14)$$

$$P_{\text{net}} = 2 \cdot 10^{-4} \cdot {T_{\text{th,in}}}^{2,49} ;\ R^2 = 0{,}9968 \quad (15)$$

Dividing the thermal water inlet temperature range into parts of 50°C, the following working fluids are prominent. Between 100°C and 150°C five different working fluids are part of the correlations: R115, R125, R218, R227ea and R236fa. In the temperature range up to 200°C the prominent fluids are R114, R115, R227ea, R236ea, R236fa and R245ca. In the third temperature section R11, R114, R123, R141b, R236fa and R245ca are found. From 250°C to 300°C only three fluids remain: R11, R123 and R141b.

So this study confirms the findings of Chen et al (2010), that R125, R141b, R218, R227ea, R236ea and R245ca are promising working fluids for supercritical ORC. But R141b is being phased out in 2020 or 2030, what has to be considered in future power plants.

The correlations between P_{net} and $T_{th,in}$, as shown in Figure 6 and in equations 13 - 15, provide a tool for project developers to assess the achievable maximum net power output of a power plant to be only by knowing the temperature of the geothermal brine. So the performance of the future geothermal power plant respectively the approximated net power output can be obtained at an early stage without knowledge of working fluids or detailed design of power plant components. In the drilling process it would even be possible to balance further drilling to reach higher brine temperatures, which is expensive, against the corresponding maximum net power output in kW.

The next step was to analyse air and water cooling and to subtract the fan performance from the net power output. The findings are that the cooling only has a minor influence if condensation and ambient temperature are constant. With rising ambient temperature the energy demand of air cooling increases exponentially. Figure 7 shows the maximum net power output of various fluids at a thermal water inlet temperature of 100-300°C, with an air inlet temperature of 15°C and a humidity of 60%. The fan performance has been considered in the net power output. The fluids contributing to this figure are: R125, R115 and R245fa in the $T_{th,in}$-range of 100-130°C, from 130°C to180°C only R227ea shows up, at 180°C to 240°C there are R114, R236fa, R245ca and R218, R123 has a good performance in the $T_{th,in}$-range of 220-300°C and R11 from 250-300°C. The trend equation that fits the data in Figure 7 is:

$$P_{\text{net}} = 1.03 \cdot 10^{-4} \cdot T_{\text{th,in}}^{2,6}\ ;\ R^2 = 0{,}9965 \tag{16}$$

Further steps in the process of this study are to look for correlations between the net power output and other power plant relevant parameters, such as $T_{th,out}$, $T_{amb,in}$, $T_{amb,out}$, $\dot{m}_{ORC}$, p_{ORC}, T_{ORC} and using power plant data from MoNiKa for future investigations.

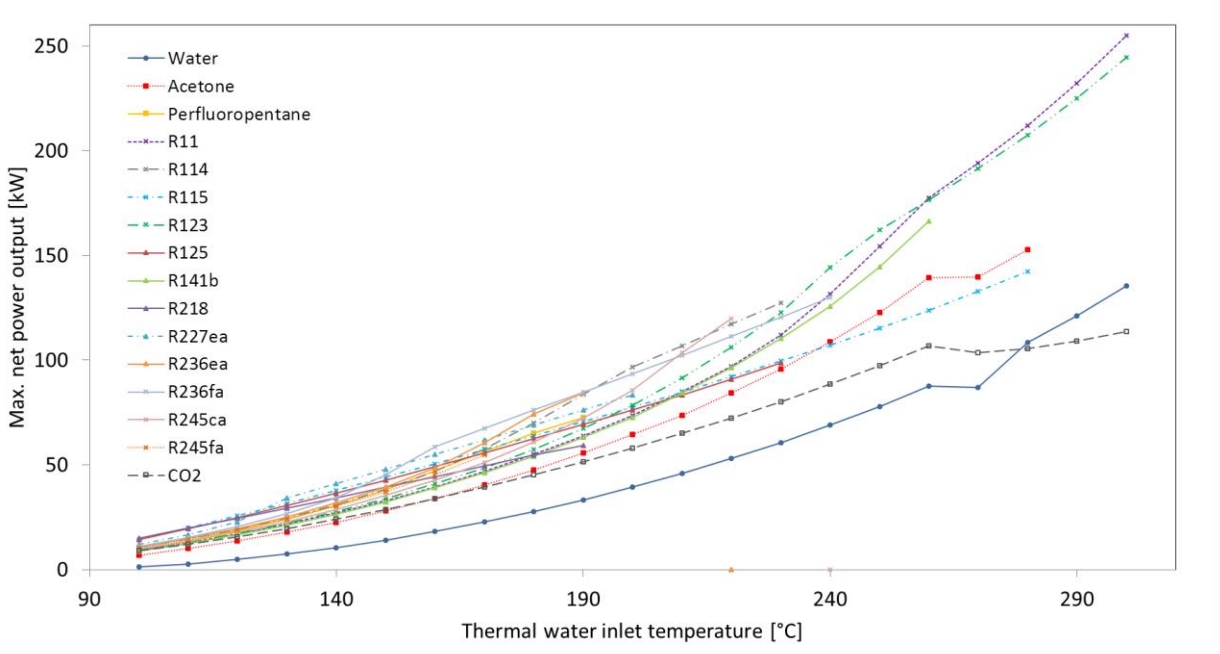

Figure 5: Maximum net power output in kW of high-performance fluids over thermal water inlet temperature in °C at a condensation temperature of 30°C, water for comparison

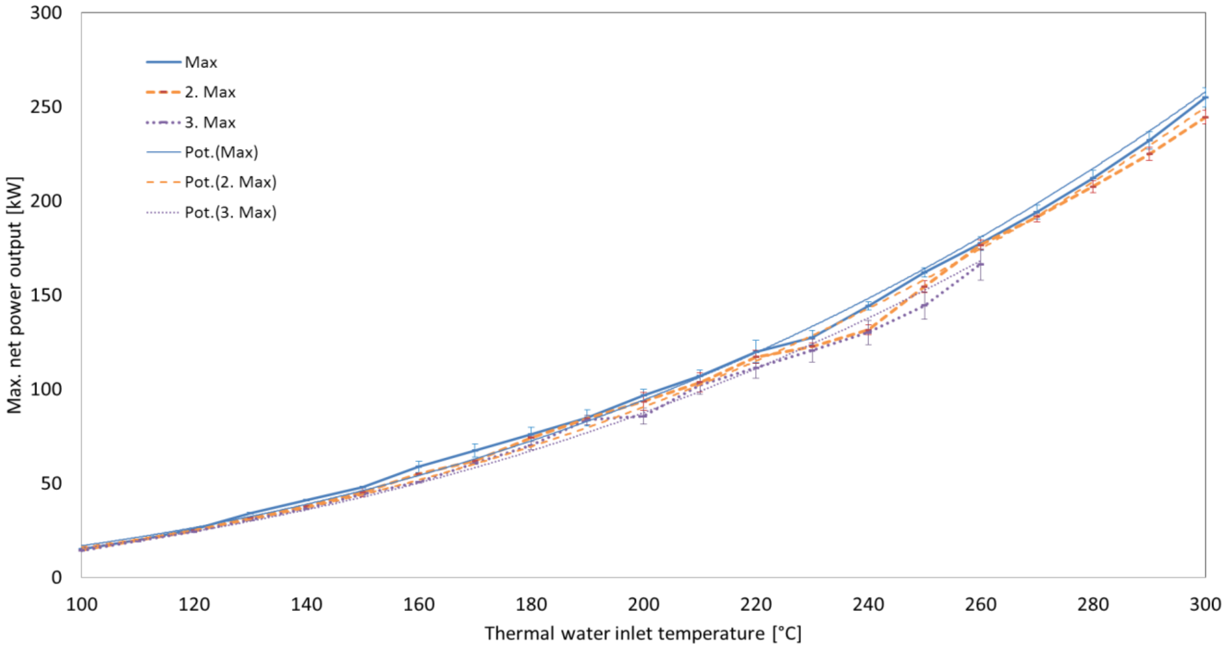

Figure 6: Correlation of maximum net power output of ORC [kW] and thermal water inlet temperature [°C] with error bars at a fixed condensation temperature of 30°C

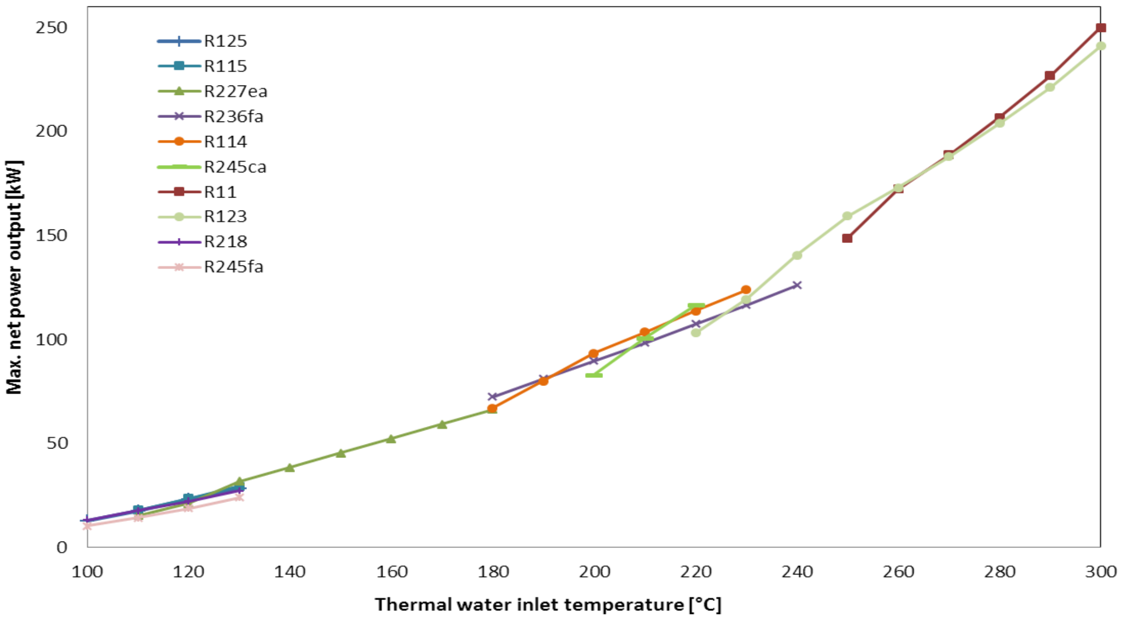

Figure 7: Correlation of max. net power output in kW and thermal water inlet temperature in °C with air cooling (T=15°C, p=0,1205 MPa, humidity = 60%) for pre-selected fluids, performance of fan considered.

6. OUTLOOK: MONIKA

MoNiKa is an acronym for mobile and modular low-temperature loop Karlsruhe. It is a pilot plant for geothermal engineering and under construction at Karlsruhe Institute of Technology (KIT), Germany. All components of the MoNiKa plant (see Figure 8) are built in containers, so that the whole pilot power plant can be transported to another location, e.g. a geothermal site. The modular design of MoNiKa enables the use of different turbines, heat exchanger modules and other components in experimental campaigns to simulate and optimize components as well as different power plant layouts. Heated water in the range of 100°C to 150°C (low-temperature) is used to simulate geothermal conditions usually found in Germany. The thermal output of this plant is 1 MW, which results in an electricity output of about 100 kW. The working principle of MoNiKa is an ORC with the following components:

A “geothermal” loop, which consists of a fuel oil tank and a heating unit to generate hot water, and a power plant cycle with propane as working fluid. The propane is pumped through a heat exchanger where it gets evaporated. The vapour is passed through the turbine to get expanded and produce electricity via a generator. After the turbine the propane passes a heat exchanger and the hybrid condenser to finally get condensed. Hybrid condenser means that usually air is used for cooling, but if the ambient temperature is elevated water cooling by spray is used additionally. Generally, MoNiKa is designed for European conditions, e.g. a condensation temperature of 30°C is assumed.

Why do we use propane (R290) as working fluid? As Vetter et al (2013) pointed out, propane is a suitable working fluid regarding a geothermal water temperature of max. 150°C and in comparison to isopentane (which is a common working fluid) it obtains a notably higher power output. It is used in a supercritical loop (see Figure 9) in order to enhance the power output and to exploit the possibilities of this innovative concept. In addition, propane is not toxic and has an ozone depletion potential (ODP) of 0 (after Ravishankara et al (2009)) and a global warming potential (GWP) of 3.3 based on 100 years (after Forster et al (2007)), which is small compared to other working fluids that have high net output at 150°C thermal water temperature. For example R115 shows a net output of 38 kW at 140°C thermal water temperature, but is harmful to the environment, has a GWP of 7370 based on 100 years and an ODP of 0.6.

MoNiKa‘s benefits are inter alia the comprehensive instrumentation for measuring pressure, temperature and flow rate at relevant points within the loop, which provides a profound data base for numerical simulations and the characterisation and optimization of main components, such as heat exchanger, pump, turbine and condenser. Another advantage is the installation of components in containers, which on one hand enables future transport to geothermal sites and on the other hand allows for development and test of custom made components. MoNiKa could even be extended to concepts of waste heat utilisation.

Which features does MoNiKa have in contrast to conventional geothermal power plants? In the water loop temperature and flow rate can be varied systematically to adapt for different site-specific conditions. In the propane loop the variation of temperature, pressure and flow rate up to supercritical conditions is possible. The feasibility of a supercritical power plant concept will be demonstrated. The comprehensive instrumentation permits deeper insights into the behaviour of components e.g. at part load. MoNiKa gives the possibility to characterise components at full or part load, which is the foundation for defining the best strategies of combining heat and power. It also contains the possibility to develop benchmarks to validate simulation tools or codes, such as GESI. The aim of all these investigations is to increase the net power output of geothermal power plants.

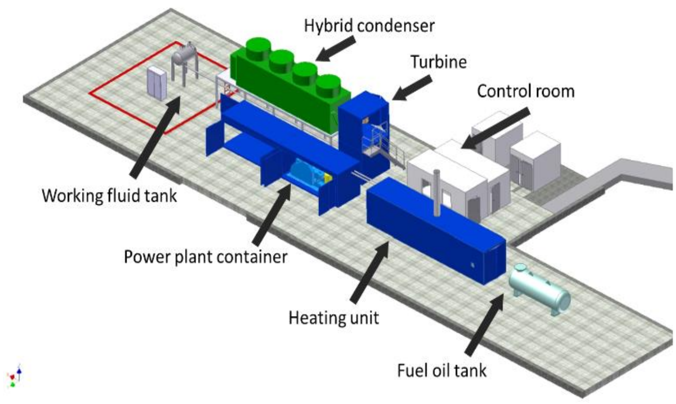

Figure 8: Layout of MoNiKa pilot power plant with all components

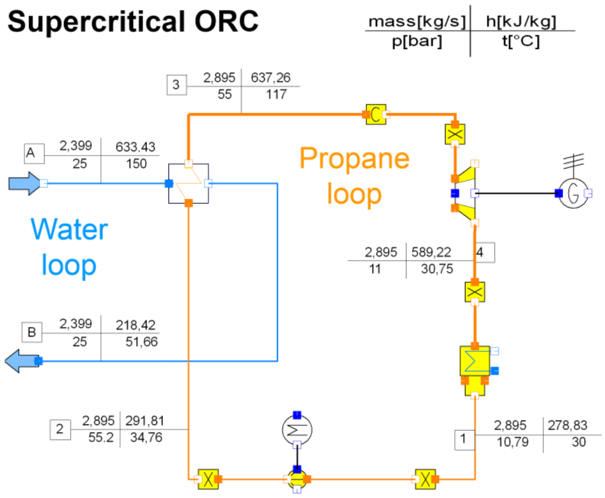

Figure 9: Supercritical ORC as used in MoNiKa

7. CONCLUSIONS

The objective of the present study is to optimize the performance of ORC power plants by developing correlations between fluid properties and maximum net power output. Therefore, the following approach is used:

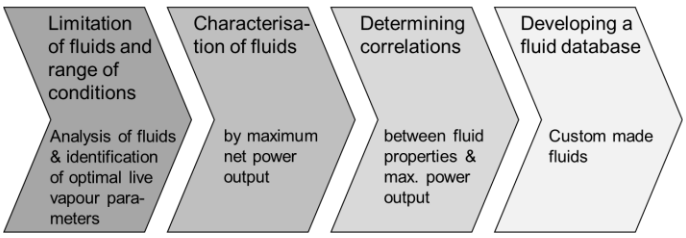

Figure 10: Flow chart for performance optimization of ORC power plants

From a vast number of working fluids available the suitable were chosen by elimination according to unfitting physical properties. From the large range of conditions the optimal live vapour parameters were selected. The analysis and characterisation of the remaining fluids was then based on their maximum net power output. In order to determine correlations between fluid properties and maximum net power output, all remaining fluids were analysed with GESI. Then a correlation (power function) between net power output and thermal water inlet temperature was obtained. Based on this findings a fluid data base will be developed as a look-up table for project developers to decide on the suitable working fluid for a geothermal power plant at an early stage adapted to the temperature of the geothermal brine. Another step will be to fathom the possibilities of custom made working fluids, so that a future project developer could order a suitable fluid for the encountered temperature of the geothermal brine.

NOMENCLATURE

h	Entropy
$\dot{m}$	Mass flow rate
p	Pressure
P	Power
Q	Heat
T	Temperature
η	Efficiency

Subscript

act	actual
amb	ambient
ap	applied
cond	condenser
cool	coolant
crit	critical
gross	gross
ideal	ideal
in	inlet
is	isentropic

is.compr.	isentropic compression
is.exp.	isentropic expansion
net	net
ORC	Organic Rankine Cycle
out	outlet
pump	Pump
re	removed
th	thermal
turb	Turbine

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