First experimental results of a supercritical Organic Rankine cycle using propane as working fluid

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In geothermal power generation, hot water is pumped at around 100-200°C from deep layers of rock in the earth's interior and converted into electrical power via a cycle process, which is usually fed into the public power grid. Electricity generation for these low-temperature cycles is nowadays usually realized in low to med enthalpy wells via an ORC process (Organic Rankine Cycle).

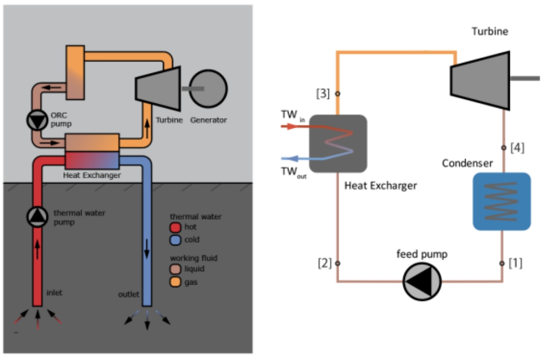

Fig. 1: ORC process

The variation of the boundary conditions and the working fluids used has a large influence on the net electricity yield and thus on the economic efficiency of a geothermal power plant.

The approach followed by the ITES-EVT group is to maximize electricity production by selecting a heat transfer fluid suitable for the site-specific boundary conditions in Europe and a supercritical live steam pressure. In previous studies [1],[3] Vetter et al. have shown that significant performance improvements are possible at supercritical conditions.

The working fluid selection has taken into account environmental and operational criteria, such as high thermal conductibility, low specific volume, high chemical stability, low corrosiveness, low flammability, toxicity, low Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) [2].

In order to optimize and validate this simulation model we built a supercritical ORC (MoNiKa).

The MoNiKa power plant

MoNiKa (Modular low-temperature cycle Karlsruhe) is a facility built at KIT campus north with the idea of studying and optimizing the ORC process. This installation is a small and compact power plant. It was designed as a modular installation to allow the study and investigation of different components and operational parameter for the research of geothermal power generation from low-temperature heat sources.

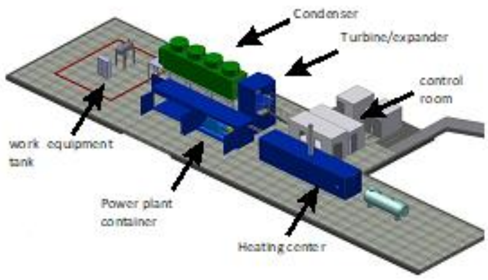

Fig. 2: MoNiKa -ORC power plant

Components description

The pumping system is compound by two pumps. The main pump is a LEWA triplex M514US G3G. It is a piston pump of max. 75 kW with a maximum mass flow of 3.6 kg/s and a design pressure of 6.5 MPa (in this will be referenced as main pump).

The heat exchanger manufactured by Gesmex, is the connection between both cycles, (thermal water and organic). It is a counter-cross-flow heat exchanger designed to work in a supercritical regime. This component consists of 200 circular welded stainless steel plates grouped in five stage. The design thermal power installed is 1000 kW for full load operation

The condenser manufactured by KÜHL-TURMKARLSRUHE has a support sub frame with 3.5 m of height. It is located between the exit of the turbine (or throttling valve), and the propane tank. However, the condenser is prepared to work with water spray. The heat exchange areas are built symmetrically in "V" configuration. They include three chambers. Each one is equipped with a vertical fan (impeller and diffusor) of 2.5m diameter. The power consumption of each motor is max.13 kW at 322 RPM, and a maximum volume flow rate of 44 m^3/s each and in total 39 kW - 132 m^3/s.

The last component of the circuit is the turbine from M+M. The axial turbine has four stages with a nominal rotational speed of 9996 1/min. The 150 MVA synchronous generator is connected to the turbine with a gearbox. The design requirements assumed an isentropic efficiency at full load of 0.8 and a vapour quality limit at the turbine outlet of 0.9.

Fig. 3:Propane tank und Condenser

Fig. 4:Main pump and Plate heat exchanger

Fig. 5: Turbine with gearbox and generator

In addition to these main components, the following auxiliary units are also important for the power plant operation.

Support pump from Grundfos, which ensures the upstream pressure to the main pump.

Propane separator from Borsig for separating the nitrogen propane mixture from the gas charged in the turbine shaft seal. The separated propane is returned to the propane tank.

Propane tank with a volume of 2.4 m³, also an additional storage tank for refilling propane.

Furthermore, we have a 7-m³ fuel oil tank to supply the heating station.

The control and regulation technology container with a redundant S7-416 PLC and the SIEMENS power plant software T3000.

The Control room container with three workstations for power plant and instrumentation monitoring.

Scientific measuring points for the acquisition of additional parameters such as ambient temperature and humidity, pressure difference condenser, temperature and velocity field condenser as well as an optical access to the propane circuit for flow characterization.

Instrumentation

The sensor technology installed in MoNiKa fulfills two requirements: the first for power plant control and regulation, the second as a platform for scientific studies conducted in the plant. Therefore, the plant is much more extensively instrumented than in a normal power plant. For balancing purposes, sensors for temperature and pressure are installed along the entire cycle, i.e., at the inlet and outlet of each component.

The mass flow rate and density of the working fluid are measured between the outlet of the main pump and the inlet of the heat exchanger using an E+H Promass 83F sensor. This sensor uses Coriolis forces and resonant frequency to provide a direct measurement of mass flow, velocity and density.

A WIKA TR34 Class A-PT100 is used to measure temperatures at all points in the system. These sensors are connected as 4-wire resistance thermometers and have an operating range of -50 to 250 °C. These thermometers are characterized by a compact design, are resistant to vibration and have a fast time response for operating measuring points. Type K thermocouples are used in areas with increased time requirements.

For pressure measurements at the MoNiKa plant we use the Vegabar 81 and 82. These pressure transmitters are universally applicable for the measurement of gases, vapors and liquids. They have a ceramic measuring cell, which allows the sensor to behave well in corrosive and hot environments. The main difference between purchased sensors is the temperature range in which they can operate. In addition, the pressure range in which they operate is different within the ORC cycle, resulting in pressure measurements in the low-pressure section having higher absolute accuracy than in the high-pressure section.

The sensors are in direct contact with the liquid (propane and water). There is no sleeve or cap between them. This direct contact allows better measurement of the fluid properties, but makes it impossible to remove the sensor from the pipeline for maintenance without first draining it. For this purpose, MoNiKa's measurement system is designed with redundancy, which means that two or three sensors of the same type are installed at each measurement point. This redundant configuration makes it possible to increase the availability of the measurement technology, which on the one hand increases safety during operation and on the other hand helps to detect systematic errors.

To measure the environmental conditions, the system is equipped with an EE33 series humidity and temperature transmitter. In addition, a set of type k thermocouples is installed in each chamber of the condenser.

Tab. 1: List of Sensors

Magnitude	Model	Measurement Range	Max Absolute error
Pressure	Vegabar81	0 to 10 MPa	0,02 MPa
Pressure	Vegabar82	0 to 10 MPa	0,01 Mpa
Pressure	Vegabar82	-1 to 10 MPa	0,01 Mpa
Pressure	Vegabar81	-1 to 2,5 MPa	0,005 MPa
Pressure	Vegabar82	-1 to 2,5 MPa	0,003 Mpa
mass flow	Promass 83F	-	0,005 kg/s
density	Promass 83F	-	0,01 kg/L
Temperature	TR34 class A	-50 to 250 °C	0,4 °C

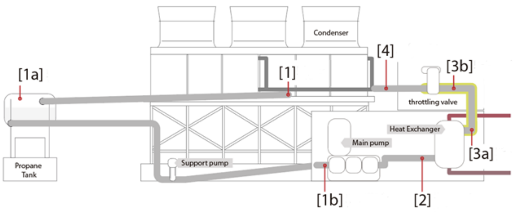

Fig. 6: Operational measurement points at MoNiKa

The accuracy of the data acquisition system is mainly affected by the analog to digital converter with a resolution of 14 bits, which corresponds to an electrical current value of ±1.221 µA.

MoNiKa's PROFIBUS has a cycle time of 100ms. The usual average data sampling time was 1 sample/ Sec. For long test runs we use 1 sample / 10 sec. because the smaller value exceed the maximal file size of the standard data export function in T3000.

Operational design parameter

The plant is a binary cycle, where the geothermal heat source is simulated. A hot water boiler with one MW of thermal power heats the water at the site, simulating the geothermal water. We are able to modify the temperature and mass flow rate at the water loop in order to have a range of input conditions and provide different scenarios. The following table shows the expected design parameter at full load operation.

Tab.2: Designed operation values.

ORC Cycle	
Propane as Organic working fluid	
Live steam point [3]	5.5 MPa and 117 °C.
ORC mass flow	2.9 kg/s
Turbine isentropic efficiency	80%
Fluid quality (at the condenser inlet)	95%
Pumps isentropic efficiency	70%
Thermal Water Cycle	
mass flow	2.4 kg/s
Temperature in	150 °C
Temperature out	47 °C
Pressure in	0.9 MPa
Power	
Thermal power:	~ 1000 kW
Heat released to the ambient	~ 930 kW
Gross Power generation	~ 150 kW
Net Power generation	~ 110 kW
Thermal efficiency	~ 15 %

Simulation Software GESI

GESI (Geothermal Simulation) Vers.2.3.6b [5] is an in-house program that has been developed in MATLAB by the ITES (Institute for Thermal Energy Technology and Safety) for studying and optimizing the thermodynamic process of the Organic Rankine Cycle (ORC). The software use the physical property data taken from REFPROP 9.0, from the National Institute of Standards and Technology [6].

This tool solve the energy and mass balance of the ORC Power Plant in stationary regime. As an input the definition of the thermal water values, selection of the operational points, the ambient characteristic and the equipment is necessary. The tool provides as result the major values of the whole process and deliver diagrams e.g. temperature- and entropy diagram.

The results of the simulation allows to validate the power plant model and to determine the efficiency of the pump and turbine in full- and part load operation.

Test run

MoNiKa is a research platform that was completed at the end of 2018. The first tests were performed in November 2019, without the turbine, operating in bypass. The focus of these tests was to investigate the entire cycle and all the components involved.

Despite the fact that the plant was fully completed, all components are installed and functional, some control loops of the control system were not fully optimized and automated at this time. This means that most of the test runs have been manually controlled.

With the turbine tests in January 2021, the entire commissioning of the plant was completed.

The optimization of the control and regulation circuits is a task in parallel to the actual test operation of the plant and will be further developed on an ongoing basis.

The first longer bypass test took place on 23.01.2020 and lasted 20 hours with an ORC mass flow of 100%,70% and 50 %. The table 3 shows the results for the 100% case.

Table 3: test run results 100% load

	Full Load 100%$\dot{m}$	Accuracy	Unit
ORC cycle			
m_{ORC}	2.87	±0.03	kg/s
$T_{AIR\ cond\ out}$	6.79	±0.75	°C
T[1]	13.8	±0.2	°C
p[1]	0.722	±0.003	MPa
T[1a]	14.3	±0.2	°C
p[1a]	0.721	±0.003	MPa
T[1b]	14.0	±0.2	°C
p[1b]	0.777	±0.003	MPa
T[2]	17.0	±0.2	°C
p[2]	5.53	±0.01	MPa
T[3a]	108.1	±0.4	°C
p[3a]	5.52	±0.02	MPa
T[3b]	108.3	±0.4	°C
p[3b]	5.50	±0.02	MPa
T[4]	14.6	±0.2	°C
p[4]	0.72	±0.01	MPa
Water Cycle			
m_{tw}	2.4	±0.02	kg/s
ρ_{tw}	0.9	±0.01	kg/L
$T_{tw\ in}$	150.2	±0.5	°C
$T_{tw\ out}$	61.74	±0.3	
Ambient			
T_{amb}	0.98	±0.75	°C
Main pump			
P_{hyd}	26	±2	kW
P_{Elec}	27.5	±0.2	kW
Support pump			
P_{hyd}	0.31	±0.006	kW
P_{Elec}	1.06	±0.02	kW
Heat transfer			
He Ex	894	±8	kW

With these measured data we can calculate the enthalpy and entropy values for the four cycle points as mentioned in Fig.1.

Table 4: Test run enthalpy and entropy results with the estimation for point 4.

ORC points	Enthalpy	Entropy	Quality
	kJ/kg	kJ/kg K	-
[1]	235	1.12	Subcooled
[2]	245	1.13	Subcooled
[3]	557	2.04	Super-heated
[4]	-	-	-
[4]* es-timated	557	2.24	0.925

At point 4 the bypass outlet/condenser inlet we have only pressure and temperature sensors. In the two phase region we need an additional parameter to define the enthalpy or entropy values.

So we can estimate the enthalpy with the assumption of an isenthalpic throttling from point 3 to 4 (bypass valve) and neglect the heat loss.

The heat transfer released from the water cycle is determined to 899 kW. The amount of heat absorbed by the propane is 886 kW with a deviation of 10 kW. This mean that we have a heat transfer efficiency of 98% ±1.5%.

Nevertheless, the total heat transfer is about 10% less than the design value. This circumstance significantly affects the performance of the entire power plant. It is not only the power generation that is affected. The biggest impact is the quality of the fluid after expansion.

The pressure loss of the heat exchanger is less than the accuracy of the pressure sensors.

The designed minimal temperature difference of the heat exchanger was 10 K and we measure a value of 33.5 K.

The total pump efficiency (hydraulic power / electric power) for the main pump was above 90% in the range of 50% -100% of ORC mass flow with a maximum value of 97%.

For the support pump, we determine the total efficiency to 29% -33%.

In order to balance the released heat in the condenser, the heat release on the airside was verified.

Using the air temperature measurement and under the boundary condition that the fans were operating at full power, the heat released was calculated and then the thermodynamic values of the state point 4.

The result is inconsistent, since from the simulations a heat release of 1100 kW was expected and in the test run we measured only about 930 kW as maximum released power.

These results show a similar steam quality after throttling and a slight sub cooling of the propane at the condenser outlet, which is not considered in the simulation. However, the difference in enthalpy and entropy is only 0.1% and does not explain the lower heat release.

Additional investigations have shown that the propane tank, due to the large propane mass, determines the condensation pressure at the condenser outlet and thus also the minimum temperature.

More detailed investigations of the condenser will be carried out in the future.

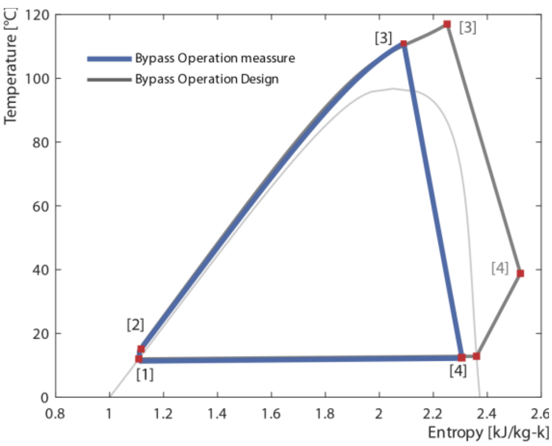

Fig. 7: Ts-Diagram of the ORC in bypass operation in comparison to the designed bypass operation.

During turbine commissioning in December 2020, significant vibration amplitudes occurred in the turbine and gearbox bearings, exceed the predefined limits and causing the turbine to trip.

Only after readjustment and replacement of the vibration sensors, it was possible to run the turbine up to nominal speed.

Unfortunately, the synchronization of the generator only worked after a manual adjustment of the excitation current controller, so that we were able to feed electricity into the grid for the first time on January 25, 2021.

In this test of commissioning, the turbine was loaded up to an electrical gross power output of 88.6 kW.

Summary

The MoNiKa cycle in stationary bypass operation was studied. As a first step, we study the installed sensors in the facility in order to determine the accuracy of the measurements.

Experiments were carried out at three operating points 50%, 70% and 100% of ORC mass flow and analyzing the behavior of the entire power plant as well as the individual components.

The 10% less heat transfer at the heat exchanger in comparison to the design values makes it necessary to redefine the optimal full load point and limit the range of operation due to the minimal allowable vapor quality at the turbine in- and outlet.

The adaption of ORC turbine inlet live steam conditions with an ORC mass flow of 2.7 kg/s, which is only 93% of the designed mass flow, is the result of the simulations performed with GESI with the corrections already discussed, and considering the limits of the thermal water cycle.

We completed the commissioning of the Monika plant with the successful power grid supply. In the further experimental operation, the focus will be on investigations and optimization of the single components and the full system performance.

References

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