ORC-DEMONSTRATION-PLANT WITH 1 KW SCROLL EXPANDER – CONCEPT, DESIGN AND OPERATIONAL EXPERIENCES

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ABSTRACT

The development and optimization of the ORC technology can be divided into two general groups of tasks and challenges: theoretical investigations and practical system and component improvement. One of the main practical challenges is the adoption of proper and effective expansion devices.

In this paper the current project – an ORC demonstration and test plant with an oil free expander - will be presented. The core of the micro power plant is a scroll-expander with a nominal power of 1 kW.
A commercially available scroll expander (Air Squared Inc., E15H22N4.25) with generator was used as expansion machine of the plant, in order to check the capabilities and the theoretical and practical limitations. In the first testing phase, compressed air has been used as working fluid in the expansion machine and the characteristic curves (electric power versus revolution speed with overall efficiency) have been plotted. These results can be extrapolated on other working fluids theoretically and are an indicator for the limitations of the scroll expander coupled with the electric generator. In the main phase of the project, the complete ORC-Installation with R245fa as working fluid is going to be tested and evaluated.
In the future the installation will be coupled to solar collectors, which will provide the heat to keep the ORC process running. Alternatively the heat can be generated by an electric driven thermal heater rated at a nominal power of 17 kW to demonstrate the functionality of the ORC itself without using solar energy. Disregarding the source of the heat, it is transmitted by two plate heat exchangers to the working fluid (R245fa). The extensive measurement instrumentation will be able to evaluate the entire process and the components used for the installation, especially the effectiveness of the expansion device.

1. INTRODUCTION

Organic Rankine Cycle (ORC) installations use an organic fluid instead of water as working fluid and are potentially feasible in heat recovery systems - especially for energy conversion on low and middle temperature levels. Many practical applications have been designed and installed to use low enthalpy heat sources like geothermal energy, industrial waste heat, solar energy, biomass combustion plants, small scale cogeneration systems, domestic boilers and others.
Within the framework of many projects and activities in the JRM-Institute and Laboratory for Energy Engineering at the University of Applied Sciences in Bremen, several practical and theoretical aspects of energy transformation using Organic Rankine Cycle have been investigated.
The prior activities focused on two general optimization and designing tasks. A special procedure and program has been elaborated and developed in the area of universal theoretical analysis, which facilitates working fluid selection in Organic Rankine Cycle for waste energy recovery from potential low and medium temperature level sources. In order to identify the most suitable organic fluids, several criteria have to be taken into consideration. An essential part of the program is a wide range database of organic fluids and the elaborated tool should create a support by choosing an optimal

working fluid for special applications and become a part of a bigger optimization procedure by different boundary conditions.

The theoretical research areas to develop and optimize the ORC technology can be divided into two general groups of tasks and challenges. The first big area is the thermodynamic system optimization which means not only the efficiency improvement within the cycle but also analysis of the complex system: heat source coupled with ORC-process (Smolen, 2014). This analysis should be performed by minimizing energy and exergy losses (Srinophakum, 2001, Invernizzi, 2007, Hung, 2001, and others).

The second theoretical field is the working fluid selection as optimization measure of the cycle and the entire process heat transfer from heat source. However, the selection of working fluids and operational conditions are very important to system performance. The thermodynamic properties of working fluids will affect the system efficiency, operation, and environmental impact (Smolen, 2011, Saleh, 2006, Angelino, 1998, Borsukiewicz-Gozdur, 2007, Liu, 2004 and others)

The ORC-Process is not the only alternative to use low enthalpy heat sources. Some technologies are available and efficient, some other technologies are still been developed but seem being promising. Among those technologies the water-ammonia cycle, the supercritical CO_2 cycle, the Stirling and Ericsson cycles, the Kalina cycle and the thermoelectric generator can be mentioned. There are many criteria and boundary conditions to compare the different approaches and methods of energy conversion but generally the Organic Rankine Cycle is preferred to those technologies, because of its simplicity and its limited number of components, all of them being very common and in the typical applications commercially available.

One of the practical limitations and challenges of developing of new ORC-installations are expansion devices, or lack of suitable machines for special applications in small and middle range of performance (especially micro- and mini ORC-installations). There are many approaches and practical solutions and technologies like using micro turbines, scroll expanders, screw machines, special reciprocation engines and others. The internal efficiency of expansion process is one of the biggest sources of energy and exergy losses which restrict system's efficiency. As example of practical possibilities and solutions, the application of a screw compressor as expansion device of ca. 30 kW has been investigated and the unique installation has been put into operation within a prior theoretical and practical work (Eicke, 2014). The project work presented in this paper deals with smaller range of performance and uses existing components in order to extend the practical and theoretical experiences and potential applicability.

2. OBJECTIVES AND REQUIREMENTS TO THE TEST AND DEMONSTRATION 1 KW ORC-PLANT

The general goal of the work was concept development, design, evaluation and optimization of an ORC plant in power range of ca. 1 kW. One of the practical intensions of the project was to investigate a commercially available scroll expander (Air Squared Inc., E15H22N4.25) with generator as core piece of the plant, to adopt the installation to this specific expansion device and to check the capabilities and the theoretical and practical limitations.

In the first stage of development, the heat source should be "simulated" by an electric heater but, as final solution, the test plant will be coupled with a solar installation in order to demonstrate the application as renewable energy conversion and use. Subject of the presented paper is only the first stage of the project and the relevant subsequent subtasks are:

- technical optimization by concept development and permanent improvement after the first operational experiences;
- thermodynamic process evaluation and optimization by using advanced measurement technology;
- theoretical validation and transfer of the measurement results to changeable temperature levels and different working fluids. (This possibility is limited by the existing installation and the reconfiguration require additional measures like component replacement);
- evaluation of the practical application possibilities in different energy supply systems.

Furthermore some additional aspects have been taken into consideration like flexibility by required modifications and improvement measures, safety aspects, analysis and prevention of operational accidents, demonstration effects and others. Advanced measurement technology should facilitate thermodynamic and technical evaluation and optimization of the plant and additionally support the demonstration effect.

3. DEMONSTRATION PLANT CONCEPT AND MAIN COMPONENTS

As already mentioned, the general goal of the installation concept has been adapted to the requirements and performance of the scroll expander (Air Squared Inc., E15H22N4.25). All components and parts of the installation have been calculated and selected, in order to use the possibilities and potential of the existing expansion device in an optimal way. The temperature, pressure and flow rate sensors have been installed in all relevant points not to be able to evaluate the whole cycle but also to validate the components and the auxiliary equipment. The connection scheme of the plant is shown in figure 1.

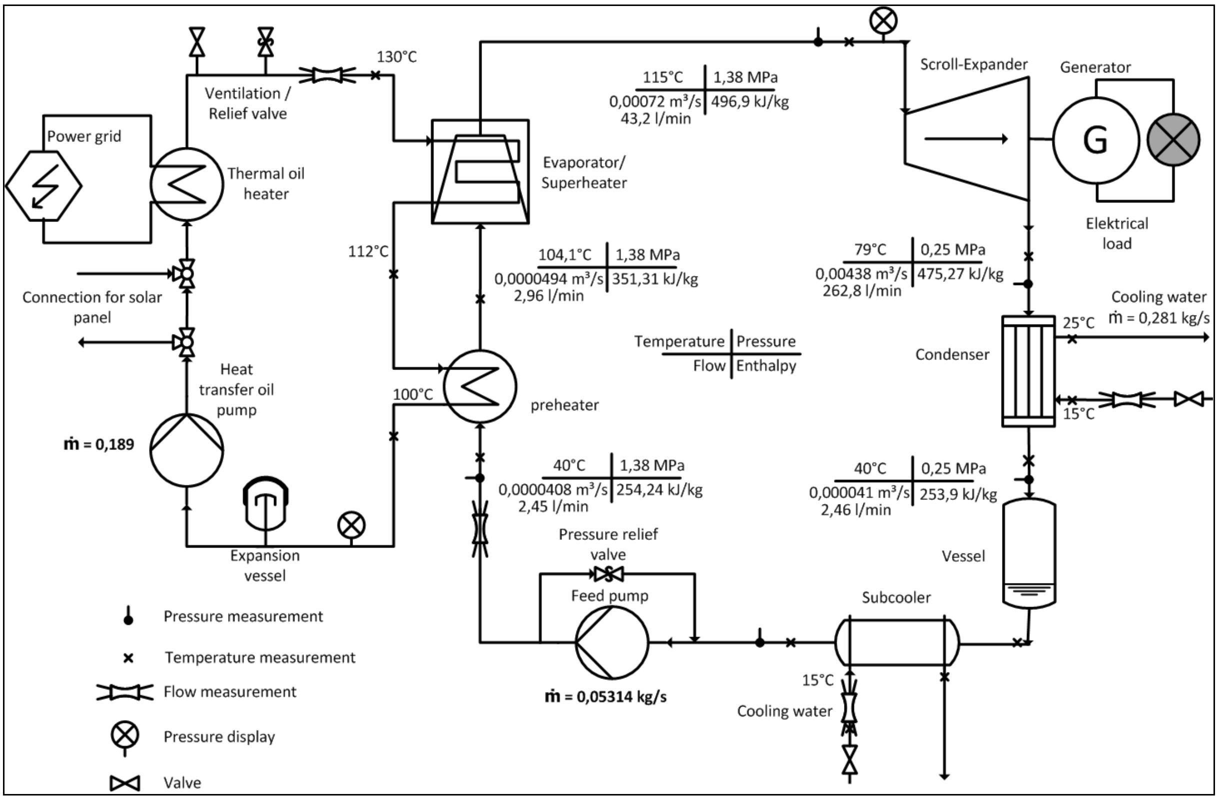

Figure 1: ORC demonstration plant – connection schema

In the first stage of the project the heat power is provided by electric heater and the heat transfer medium is thermal oil. The typical ORC-installation consists of preheater, evaporator, scroll expander, condenser and feed pump. An additional special part is the refrigerant sub cooler after the storage tank. This one facilitates the operational quality, especially by putting into operation or changeable performance (experiences from the bigger installation mentioned in the introduction).
The thermodynamic cycle is shown in figure 2 (log p–h–Diagram).

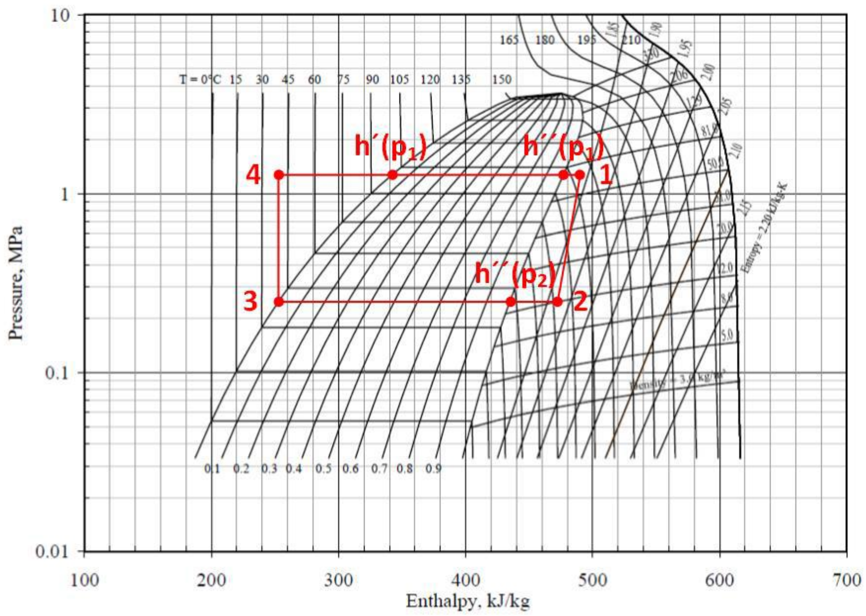

Figure 2: ORC cycle parameter in log-p-h-diagram

For the test bench the working fluid R245fa was selected but some alternatives are possible and can be taken into consideration. The calculated (expected) efficiency amounts to ca. 8.7 %. This efficiency has been calculated as total efficiency, it means electrical energy output to thermal energy input (4-1 in Fig. 2). The expected internal efficiency of expansion (1-2 in Fig. 2) has been considered as well as pumping power (3-4 in Fig. 2). Heat losses in heat exchangers (evaporator, condenser) and in connecting pipes are negligible - when good insulated - and were not calculated.

The following table specifies some important data and characteristics to the main components of the installation.

Table 1: Components of the plant – selected data and characteristics

No.	Component	Parameter
1.	Scroll expander	Air Squared Inc., E15H22N4.25, expansion ratio 3.5
2.	Generator	AB30 Hydro, 50Hz, 2400W at $3000 min^{-1}$
3.	Electric thermal oil heater	Typ HF/SE-20, t_{max} = 130°C, Power = 20kW
4.	Feed pump (refrigerant)	Slide pump with magnetic coupling
5.	Heat exchanger	Preheater: Plate heat exchanger, GPL 25-8 Evaporator: Plate heat exchanger, GPL 25-14 Condenser: Plate heat exchanger, GPL 1-20 Sub cooler: Pipe in pipe heat exchanger Typ HE1.5
6.	Heat transfer pump	small centrifugal pump for Therminol ADX10
7.	Electric installation (energy use)	15 Halogen bulb each 100W electrical load

4. DESIGN OF THE INSTALLATION

The installation has been designed and built in the Laboratory for Energetics of the Hochschule Bremen within a master project work (Haberkorn *et al.*, 2015). All the requirements and objectives mentioned above has been considered and as demonstration effect the front side of the box shaped stand is designed as thermodynamic part, the expander and generator is mounted on the top and the electric and control devices are placed on the back – as shown in figure 3. On the right the electrical power can be visualized by luminous halogen lamps, which are controlled by a special board. For the second stage of the project, the connections to the solar installation have been designed too.

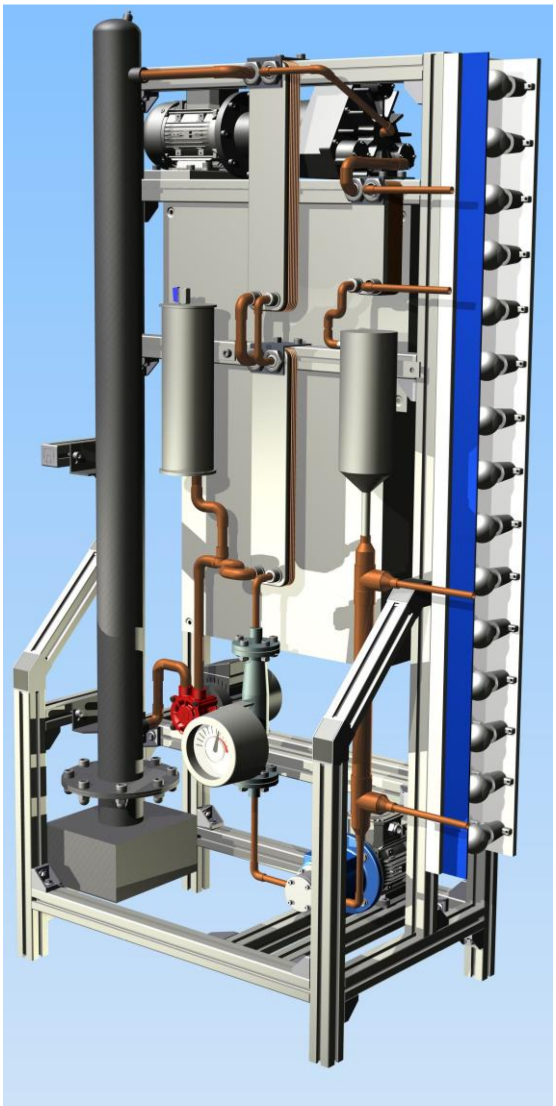

Figure 3: Design of the 1 kW ORC demonstration plant

5. LABVIEW CONTROL SYSTEM

This ORC-plant is developed to demonstrate a steam cycle and to show the function of its components. A Data Acquisition System cDAQ 9178 was used for measuring the temperature and the pressure in each condition, the electric power, the volume flow and the revolution of the scroll expander. This system is built up in a modular way and cause of the integrated signal condition the sensors are clearly arranged and direct connected. The voltage and current flow of the generator are converted by a hall effect transducer into a signal of up to 5 Volt so that the effective electric power could be calculated. The measurement equipment is shown in figure 4 and is located in a separate switchboard to reduce electric noise from inverter and motor.

To hold the required voltage and the frequency, for example 230 Volt at 50 Hz, a LabVIEW program calculates the electric load and turns on additional light bulbs or switches them off (each light bulb has nominal 100 Watt at 230 Volt). A maximum number of 15 light bulbs can show directly the produced power of the specific operating point.

The software searches for the measured temperature and pressure the values for enthalpy and entropy to the main condition points from a table. Additional to the heat power, the electrical power, the revolution and the efficiency these points are also visualized in a h-s-diagram and a T-s-diagram.

The speed of the feed pump is controlled over an inverter, shown in figure 4, to steer the mass flow of the refrigerant in the cycle to hold the evaporating temperature on one hand and to control the revolution of the scroll expander on the other hand.

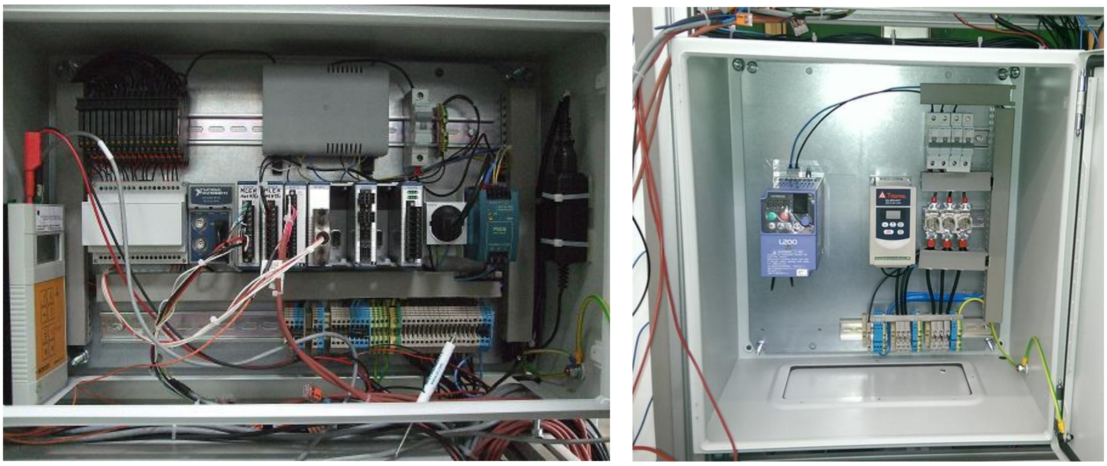

Figure 4: The measurement equipment (left) and frequency inverter to control the feed pump (right)

The electric thermal oil heater was not delivered in time, so that the scroll expander was tested with compressed air to check the control loop, the sensors and the electric load.

6. COMPRESSED AIR TEST BENCH FOR SCROLL EXPANDER TESTS

The test bench was enlarged with air pipes and an air flow meter to test the scroll expander and the generator. The supply grid for compressed air of the Laboratory for Energetics is limited to 0.95 MPa therefore it was not possible to test the expander with the maximum pressure of 1.38 MPa.
In the beginning the characteristic of the generator (voltage versus speed) was measured. The first run showed that the generator is self-excited and built up a magnetic field when the break-through-voltage of the diode is over 100 Volt the first time – like shown in figure 5. The following tests show a useful voltage of 80 Volt when the revolution per minute is higher than 1500 min^{-1}.

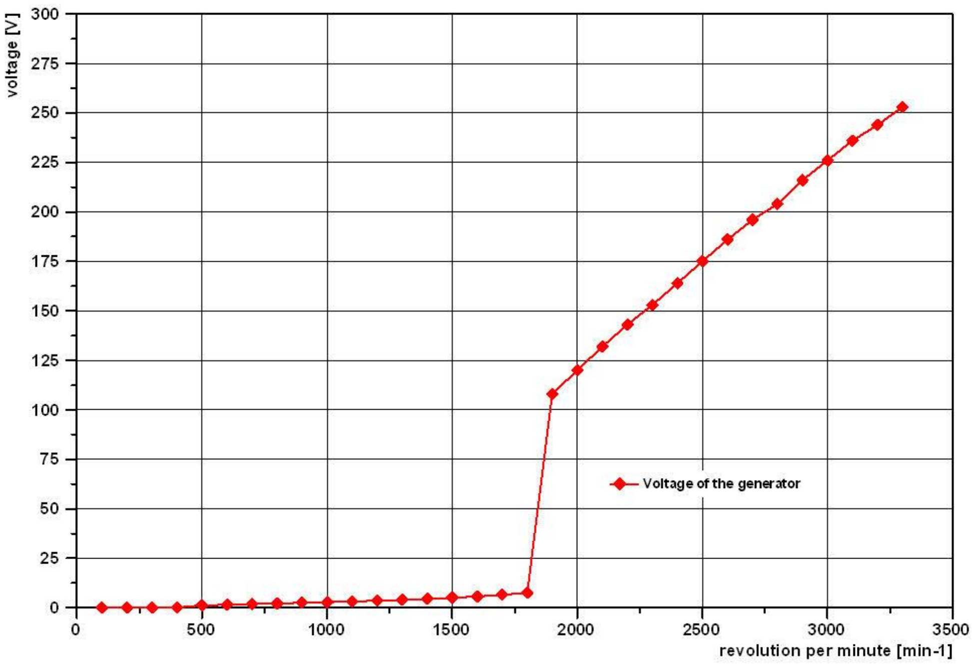

Figure 5: Characteristic of the generator Voltmaster AB30 2400 Watt **-** voltage vs rpm

The compressed air is expanded in the scroll expander from an inlet temperature of 19°C with a volume ratio of 3.5 to a low temperature of 10 degrees below zero at the end of the expansion that the duration of the test is limited not to risk a damage of the expander. The enthalpy and the thermal properties of the air is not comparable with the 115°C hot refrigerant of the real fluid. It is therefore necessary to increase the load of the test bench at lower revolutions per minute by external excitation of the rotor to measure the full curve of the electric power. The real refrigerant fluid with its higher energy content would cause higher speeds of the scroll engine than for air operation and is therefore in the correct speed range. Figure 6 shows the electric power versus revolution per minute for a pressure from 0.50 MPa to the maximum of 0.94 MPa. The overall efficiency is noted in numbers at every second point. The volume flow through the scroll engine increases with the increase of speed but the torque goes down to zero at maximum speed. The efficiency is higher with higher suction pressure and rise up to a maximum value a little bit higher than the half of the revolution per minute with no load. For example the efficiency for a pressure of 0.94 MPa at 3600 rpm is zero and rise up to η = 0.43 at 2200 rpm.

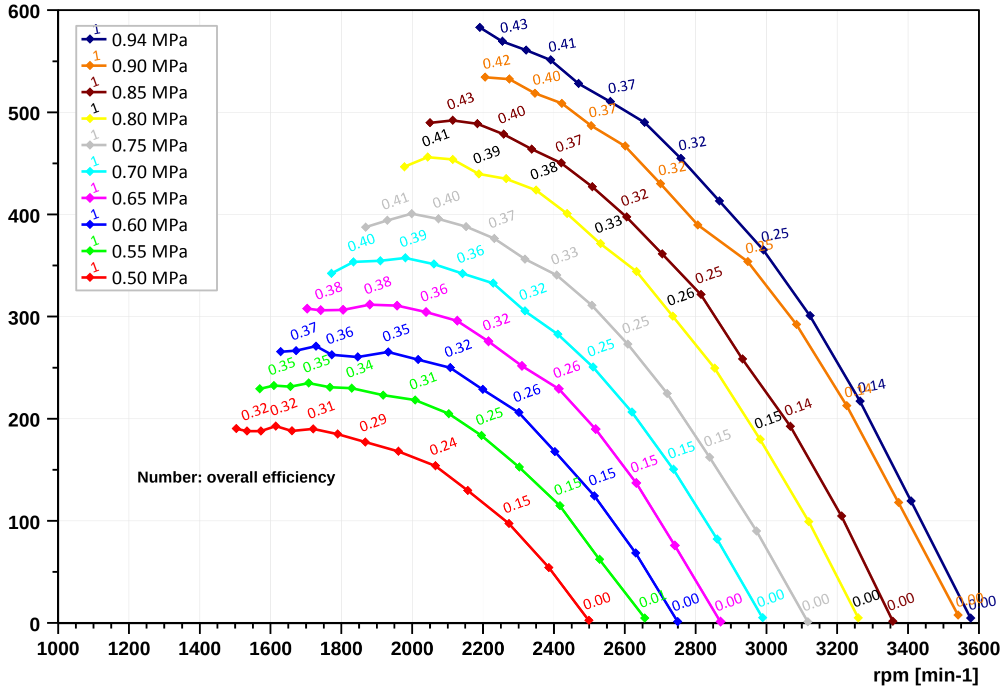

Figure 6: Electric Power versus rpm with overall efficiency

7. CONCLUSIONS AND OUTLOOK

As result of the practical orientated work, a unique 1 kW ORC installation on the base of scroll expander has been developed, designed and built, which facilitates process improvement and demonstration effects. Additionally, a test bench for scroll expander tests with pressurized air has been developed and equipped in order to investigate operational features of the expansion device as the first practical step. These preliminary tests are essential for the subsequent thermodynamic process improvement and optimization. The final presentation is going to include the first operation experiences and test results.

Related to the second stage of the ORC project a solar installation has been calculated and planed, which is going to be installed and coupled with the ORC-plant to extend it to a complex installation using a renewable energy source.

Parallel to this technical project, an additional aspect – namely economical one - has been taken into consideration by investigating the practical applicability. One concrete application possibility of the 1 kW plant for waste heat use from an industrial process was evaluated from economical point of view, in fact with a negative result. (The economic efficiency calculations have been conducted for German energy prices and economical boundary conditions and the calculation's details would be beyond the scope of this paper). The main reason for the economic ineffectiveness is of course the costs of the unique installation, which cannot justify profitable operation under the terms of conventional economy.

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