Screw Engine as Expansion Machine Applied in an ORC-Test-Installation - the First Operating Experiences

Lubrication system for a screw machine in reverse rotation

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Introduction

The waste heat from different energy transformation and production processes becomes nowadays an enormous energy amounts and can be used as a secondary, low enthalpy energy source by different means and methods. The difficulty of capturing, distribution or transformation into other forms of energy comes from the thermodynamic characteristics of the heat and the high costs connected to the equipment needed to use or transform it into useful energy.

One candidate suitable for improving efficiencies of existing applications and allowing the extraction of energy from previously unsuitable sources is the Organic Rankine Cycle. Applications based on this cycle allow the use of low temperature energy sources from industrial applications, geothermal sources, biomass fired power plants and micro combined heat and power systems [1 through 4].

As result of a previous theoretical research work about effective low enthalpy energy use from biogas installation a special ORC-concept has been developed and analysed [5], [6]. The main features of the concept are two heat input stages and two expansion stages corresponding to the heat transfer temperatures and ratios in the exhaust gas heat exchanger of a combustion engine (specifically a gas motor in a biogas plant) and in the cooling system of the engine. In order to optimize the pressure ratios and thermal efficiency, the high-pressure expansion is carried out in a micro-turbine, and the residual expansion on the lower temperature and pressure level - in a screw engine.

Though, a big practical challenge is the adoption of proper and effective expansion devices for the ORC-Installation.

The development of a lubrication system and the first operating experiences from the test installation are the main topic of the proposed paper.

Test installation

Parallel to the theoretical investigations and optimization work a practical research has been planned and carried out [7]. The biggest practical challenge is the adoption of proper and effective expansion devices for the ORC-Installation. Relating to the theoretical concept a special test bench has been developed and assembled in the Laboratory for Energetic of the University of Applied Sciences in Bremen – like shown in Fig. 1. The thermal parameter and data represented in the diagram correspond to the design data of the components and can be varied during the practical operation of the plant. The heat input is simulated (as waste heat source) by a thermal oil boiler, which supply the preheater and the evaporator.

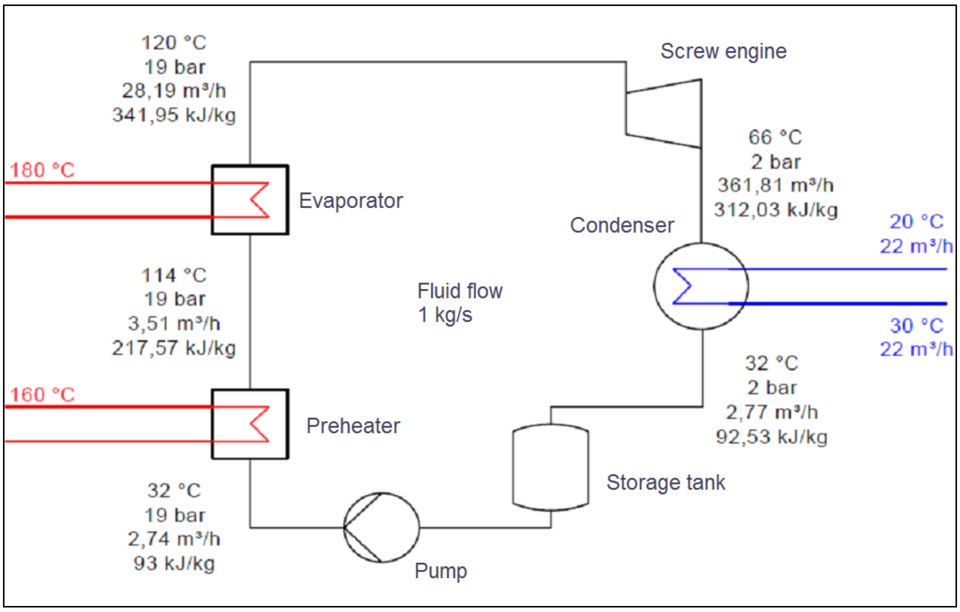

Fig. 1: Circuit diagram of the ORC-Process in the test bench installation

The whole installation is equipped with the measurement instrumentation controlled by the software LabVIEW. The regulation is still manual and makes it possible to collect experiences by placing into service and steady-state operation. In order to facilitate the practical operation and to separate the thermal installation from the expansion device an expansion valve has been mounted as by-pass of the screw engine. On this way the putting into operation is easier and the whole installation more flexible.

The main goal of this installation is testing the operation of expansion machines, especially screw engines. For this purpose a Variscrew VMY 046 HR refrigerant screw compressor has been used, chosen from the product range of the manufacturer ‘Aerzen’. In order to use a compressor as expansion machine some important modifications are essential, which have been developed and implemented.

Modifications of the screw engine installation used as an expansion device

Screw engines have some special features which turbine engines don’t have [8]. In order to operate a screw compressor as an expander, only the direction of rotation has to be reversed. Unlike turbine engines, design differences to optimize them for either function are minimal. Rotor tip speeds of screw engines are roughly one order of magnitude less than those in turbine engines. Therefore, screw engines can usually be directly coupled to normal 2 and 4 pole generators which reduce transmission losses. Because of the low fluid velocities, the presence of liquid in the working chamber does not damage the rotors, so the screw engine can expand in wet vapor as well. This can give more possibilities how to run the process which can result in more efficiency of the total process. At last, due to the reason that a screw engine is resisted to liquid in the working chamber, it can also improve performance by sealing the gaps with a liquid and acting as a lubricant. In most situations this liquid is lubricating oil which fulfills the viscosities requirements. The application of screw engines as expansion devices has been investigated by many practical and theoretical works [9], [10], which report some positive results but on the other hand many questions and practical tasks stay still unsolved. This is the approach to use a commercial screw compressor and to modify it for the purposes of an expansion machine.

Lubrication-Installation in a screw engine

Lubrication in a machine has three main effects, namely:

- reducing friction
- cooling and
- sealing gaps

Reducing friction is important to keep a high lifecycle. These are mainly the friction between the rotors and the friction of the bearings. Since cooling has a negative influence on the efficiency of an expander, this effect of lubrication has to be prevented from incidence as far as possible. However, the lubrication of the sealing gaps can also have a positive effect on the efficiency of the screw engine. The Oil-injection for the lubrication will cause a higher hydraulic friction between the rotors and will cause for example a half rotation speed. However, the pressure discharge can even get three times bigger due to the lubrication of the rotor gaps.

For the lubrication of it, the system needs some adjustments to operate correct as a screw engine. Since screw machines are mainly used as a compressor, well known lubrication systems are only available for screw compressors. Therefore the lubrication system of a screw compressor is taken as an example for the lubrication in the test plant with the additional information from Aerzen. A simplified diagram for the lubricant flow of the test bench is shown in Figure 2.

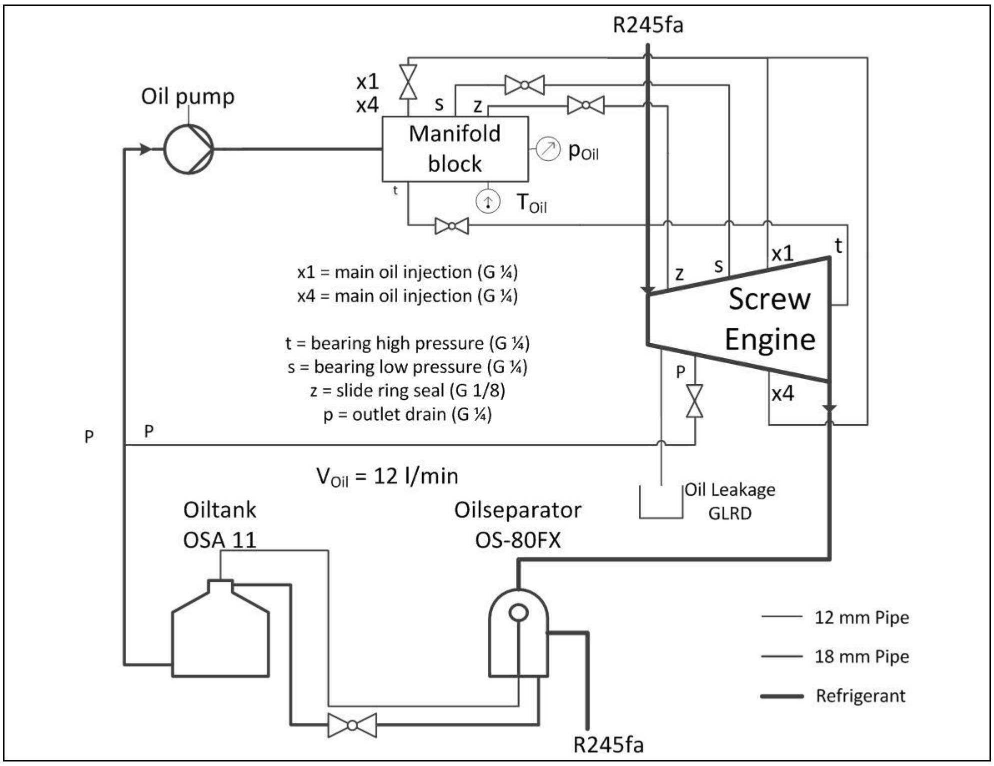

Fig. 2: Lubricant flow of the test bench screw engine

Due to the negative input of lower temperatures for the efficiency of a screw engine, the oil cooling heat exchanger is removed from the compressor concept. The oil separator which is directly after the screw engine has now a low pressure instead of a high pressure with a screw compressor. Therefore the oil pump is now necessary in order to pump the oil up again to its highest pressure inlet. This pressure inlet is close to the high pressure inlet, so the pressure difference in the oil pump has to be almost the same as the pressure difference in the screw engine. An outlet was also added to the lubrication diagram for the Variscrew VMY 046. This outlet is a drain outlet (connection “p”) which can function as a bypass for starting of the screw engine.

The volume flow which is given by the manufacturer is summed up to 60 l/min. In comparison to the flow of the refrigerant (60 kg/min) are these high values that are suitable for the operation as a screw compressor, which are probably over dimensioned to ensure its security. Therefore one has to find out in the test bench how low a volume flow without cooling the system can possibly handle. This is important because the less heat losses due to lubrication occur, the higher the efficiency will be.

When a lower volume flow is set, it has to be ensured that the viscosity of the lubricant will still be sufficient. When the temperature of the oil rises, the viscosity will decrease. According to the specifications of Aerzen, the allowed viscosity during operation is between 12 and 50 mm^2/s. This can be realized by choosing the right lubrication oil.

The first operational experiences and characteristic diagrams of the modified screw engine installation

A Variscrew VMY 046 HR with a flow of about 1,04 m^3/min is installed. To get a high pressure ratio from 1,9 MPa to 0,2 MPa a profile combination of 4 male to 6 female without synchronisation wheels is build in. The male rotor is connected with a coupling to the generator brake also for measuring revolutions per minute and torque. For cooling the refrigerant in a compressor it is calculated 40 l/min flow of the lubrication. The tests started with a reduced flow from 60 l/min to 15 l/min generated in a rotary displacement pump. To guarantee that the sealing and the bearings are well lubricated the main oil injections (x1 and x4) for cooling are completely closed.

The different refrigerants have different vaporisation points and have an effect on the efficiency of the total process. Caused of the low temperatures of the waste heat source the cycle is filled up with the suitable refrigerant R245fa. The superheated vapour flows from the bottom up to the outlet above through the screw engine like it is shown in Figure 3. The injected oil is filtered out in the oil separator next to it, to keep the refrigerant cycle especially the heat exchanger clean.

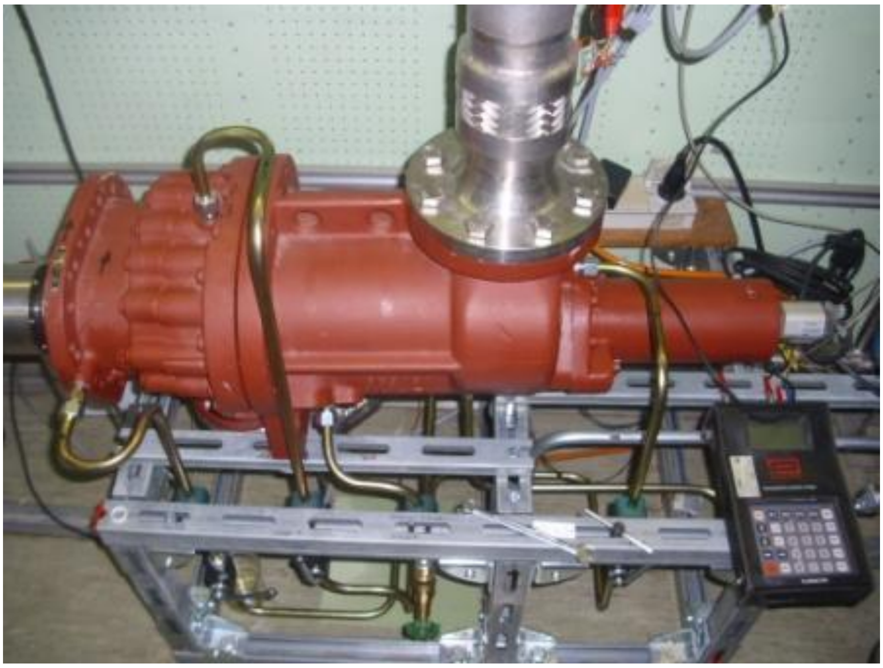

Fig. 3: Screw machine Aerzen Variscrew VMY 046 HR V_N: 1,04 m^3/min at 3025 min^{-1}

Due to cavitation problems in the feed pump, the target pressure of 1,9 MPa was not achieved in the beginning of the tests. In Figure 4 a measured process cycle is shown in a diagram ‘temperature versus entropy‘. This process is shown by the red solid line.

The organic fluid is heated up in a preheater and superheated in a second heat exchanger to t_1 = ~115 °C at p_1 = 1,1 MPa and is expanded in the screw engine to t_2 = ~80 °C at p_2 = 0,16 MPa. The exhausted vapour is condensed in a fluid-fluid tube heat exchanger at a temperature t_3 = ~25 °C.

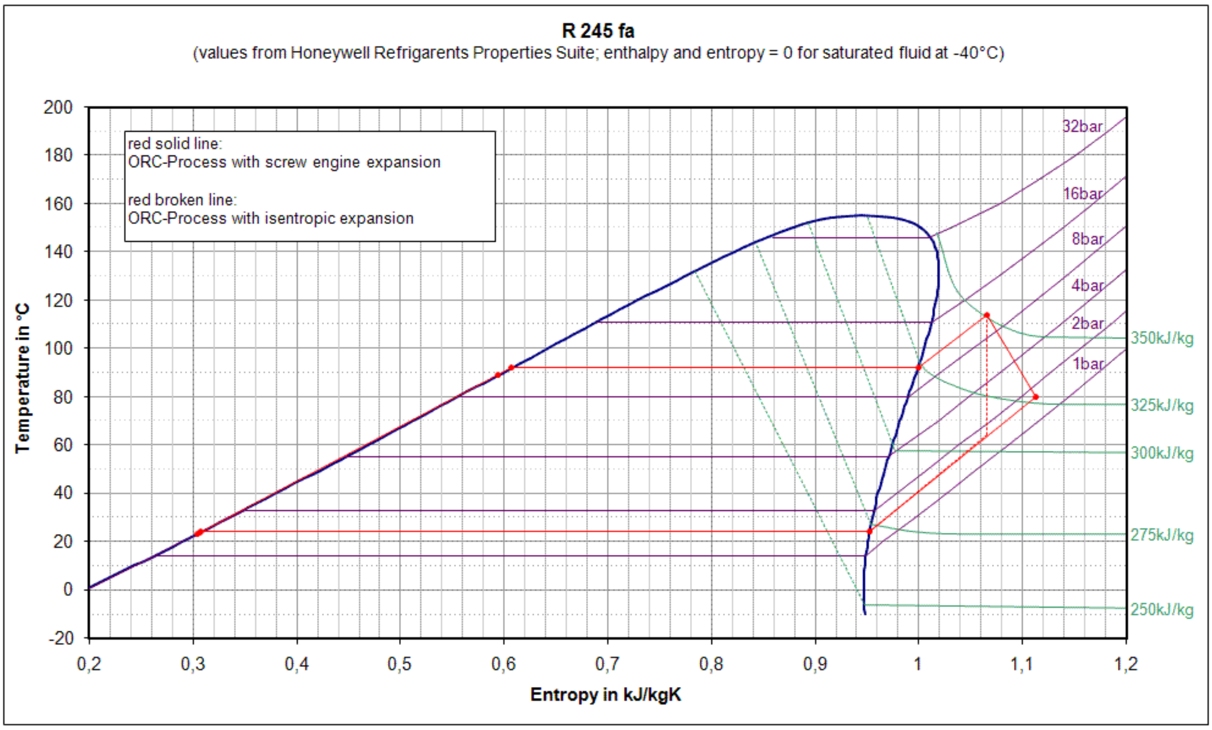

Fig. 4: ORC-Process with 1,1 MPa at 113 °C overheated, power = 17,6 kW at 2500 rpm

The red broken line is the theoretical isentropic expansion which is necessary to calculate the inner efficiency of the screw machine by dividing the enthalpy difference of the real expansion by the isentropic enthalpy difference.

The inner efficiency varied in this screw machine between 0,45 and 0,6 for different pressure at the entrance of the expansion machine. The mass flow multiplied with the difference of enthalpy gives the power and is nearly equal to the mechanical power measured direct on the generator.

The characteristic curves of the measured mechanical power versus revolution per minute are shown in Figure 5 for different feed pump operating points which cause different pressures in the system.

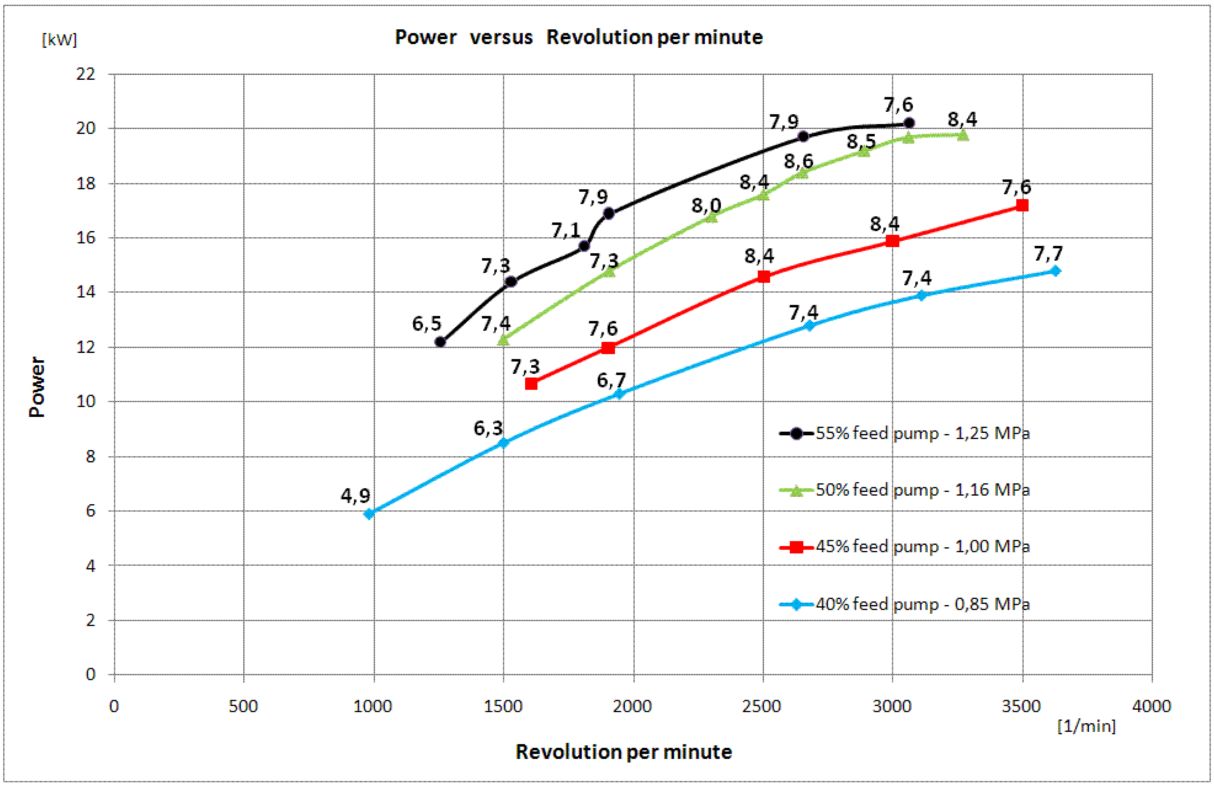

Fig. 5: Mechanical Power by different pressure of the feed pump operating points

A higher pump capacity point of the feed pump means on one hand a higher pressure but also a higher mass flow in the plant cycle and therefore a higher power of the unit. The overall efficiency of the plant is between 7,5 % and 8,5 % at 2500 rpm and 3000 rpm.

This efficiency appears to be very small, but in comparison to the Carnot-efficiency for a waste heat source at low temperatures of round about 15% it is very good.

Perspective of an ORC-plant and the test bench

The total efficiency of a combustion engine in a biogas plant could be enhanced very well in combination with an Organic Rankin Cycle plant with a screw machine.

The next steps are the insulation of the pipes and the engine itself to decrease the thermal losses and to increase the overall efficiency. Also it has to be investigated if a higher flow of the lubrication oil will have a good effect on the gap between rotor and housing and therefore a better inner efficiency.

Conclusions

The commercial and technically mature technology of screw machines as compressors can be adopted and used in reverse (expansion) but not without technical challenges and problems. The most important goal and challenge is the design and construction of the lubrication system, which has to perform two tasks – reducing friction and sealing gaps. First of all the cooling effect and requirement of oil is not the same when using an expansion device (opposite direction of mass flow and pressure conditions) and the oil mass flow can be reduced, namely without disturbance of other functions.

The first operation experiences provide promising results and encourage further investigations.

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