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Simulation and Thermodynamic Analysis of a Two-Stage Organic Rankine Cycle for Utilisation of Waste Heat at Medium and Low Temperature Levels

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Abstract: A two-stage ORC process is proposed as a technical option for utilising waste heat from power generation processes in combustion engines, and specifically as an efficient means of increasing the total efficiency of energy conversion in existing and projected biogas plant. Due to process-related factors, the utilisation of waste heat in the exhaust gas heat exchanger and from the cooling system of the combustion engine is performed at different temperature levels and is realised in the ORC process in two stages by means of a micro-turbine and a screw engine. In the course of the research work conducted, a complex calculation and simulation program was designed and created with which thermodynamic analysis as well as, to some degree, operational analysis of the respective processes were carried out.

The novelty of the concept developed here consists in adapting the framing conditions of a two-stage ORC process to the demands posed by utilizing the waste heat of biogas plants and to the practical application possibilities with respect to pressure ratios and temperature levels of expansion machines. The concept has been thermodynamically investigated and the results form the basis for constructing a test installation which shall enable the verification of these theoretical results.

Key words: Low temperature energy use; Organic rankine cycle; Two-stage process

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Nomenclature

A	heat transfer area, m^2
c	specific heat capacity, W/(kg K)
h	specific enthalpy, J/kg
$\dot{m}$	mass flow rate, kg/s
k	heat transfer coefficient, W/(m^2 K)
p	pressure, Pa
P	performance (mechanical), W
s	specific entropy, J/(kg K)
$\dot{W}$	heat capacity of a working fluid, W/K
ϑ	temperature, °C
Δ	symbol of increase
ε	performance number of a heat exchanger
η	energy efficiency

Subscripts

1	inlet
2	outlet
I	related to the preheating part of the evaporator
II	related to the evaporation part
EGHE	related to the exhaust gas heat exchanger
SHE	related to the engine cooling system (system heat exchanger)
ORC	ORC working fluid
P	constant pressure
PP	pinch point
SE	related to the screw engine
T	related to the turbine
th	thermal oil

1. INTRODUCTION

Given the growing scarcity of primary energy resources, achieving increases in the efficiency of energy conversion processes is one of the key challenges, because it enhances the efficiency of the whole energy conversion chain and hence leads to an optimized use of primary energies. From this perspective, low-temperature heat or waste heat from various processes is becoming more and more “attractive” as a secondary energy source. In the course of our own research work on optimising the total energy utilisation ratio of cogeneration units with combustion engines [1], problems regarding the efficient utilisation of waste heat arose that appear particularly acute in the case of biogas installations. Most biogas plants in Germany operate as combined heat and power systems, yet the utilisation of waste heat is non-optimal and in many cases is limited only to utilisation of thermal energy for the biogas generation process, while the remaining heat is either not used at all, or only partially. In terms of total energy utilisation ratio, this situation is dissatisfactory and results primarily from the fact that there are no major consumers of thermal energy in the vicinity of biogas plants which have a suitable and continuous requirement for thermal energy.

A representative circuit diagram of biogas installation with gas engine, turbo charger and air-gas ratio cooling unit is shown in Fig. 1. It is only one of the possible variants. The waste heat can be used from the exhaust gas heat exchanger at the higher temperature and from the “system heat exchanger” and possibly from the gas cooling unit at the lower temperature level.

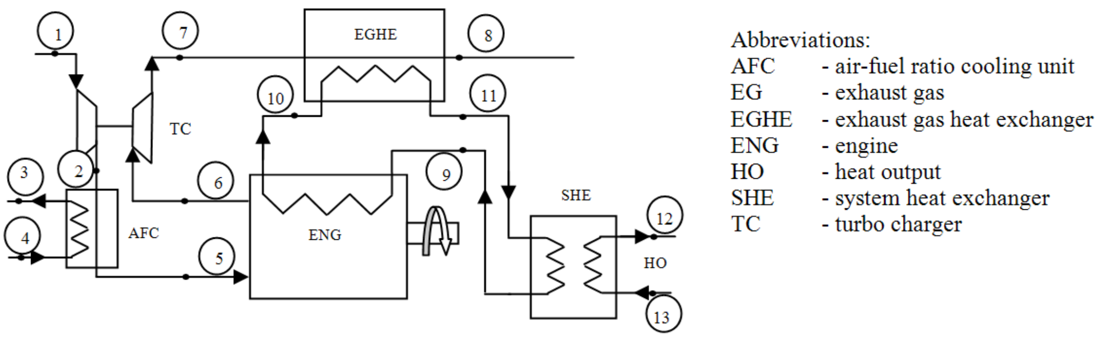


Fig. 1: Representative circuit diagram as an example of biogas installation

In these circumstances, optimising the biogas plants by converting the waste heat into electricity in an ORC process at medium or low temperature is a relatively complicated and cost-intensive solution due to the investment involved [2], it is, however, one that leads to a marked increase in efficiency, and thus is, given the conditions described above, the only conceivable alternative.

ORC research is a relatively new area of research, although due to the growth in environmental standards in companies and the associated possibility of using ORC systems, practical development of the requisite plant engineering techniques is intensifying and in some cases is being applied, as presented at an international conference organised by our own institute [3, 4, 5]. Current research trends can essentially be subdivided into three sub-areas, namely ORC system engineering, working fluids and process simulation. Due to the enormous practical relevance of this technology, there are some complex overlaps between these three sub-areas with regard to the optimisation approaches that are taken.

Most theoretical and practical research work deals with the investigation and optimization of one-stage ORC processes [e.g. 6, 7, 8]. Apart from that there are research projects which propose rather specific concepts, investigating for instance multicycle ORC engines [9] or possibilities of implementing an absorption heat pump in combination with a Clausius-Rankine cycle [10].

In the course of the work presented here, parametric examination of an ORC concept is being carried out that clearly pertains to be used in biogas plants, and specifically one that involves the utilisation of waste heat at two different temperature levels, that is in the exhaust gas heat exchanger and from the cooling system of the combustion engine. The two combined expansion stages are to be realised in a micro-turbine and a screw engine [11]. A similar idea for a two-stage process but with another coupling concept and different framing conditions was presented in paper [12].

The research demand resulting from practical applications mainly consists in investigating the complex processes in a two-stage ORC cycle with two different expansion machines and different mass flow rates in the two linked parts of the complete system. The primary focus of this paper is on thermodynamic and operational analyses; practical aspects are currently being examined as well (design and development of a test bench).

2. ORC SYSTEM CONCEPT

The ORC system concept also mentioned in the introduction comprises two heat input stages and two expansion stages. The two temperature levels of heat input correspond 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. High-pressure expansion is carried out in a micro-turbine, and the residual expansion is coupled to expansion of the working fluid from the low-temperature heat input in a screw engine. Although this complicates the system as a whole, it permits better operational exploitation of the options provided by the two expansion machines. The general overall concept for the ORC system is shown in Fig.2.

It should be emphasised that the manner in which the installation operates involves many operational engineering challenges and aspects which need to be solved during practical experiments, and which are not addressed in the present paper. Mention is merely made of the fact that the ORC concept is primarily suitable for stationary operation, due to the problems in regulating the expansion machines and the installation as a whole. Biogas plants usually operate under steady operating conditions, however.

Fig. 3 illustrates the process schematically in the form of a T-s diagram in a simplified version in which the isentropic pressure rice in the both pump stages is assumed. The possible alternative is the throttle valve as a pressure reduction stage.

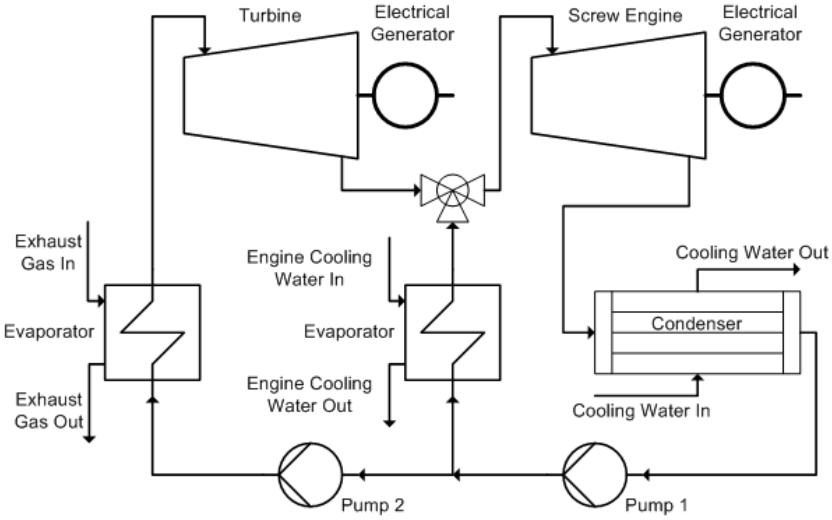


Fig. 2: Overall concept for a two-stage ORC system

Both variants (with and without a pressure reduction stage) have been considered as part of the detailed analysis. The variant with two pumps is more efficient and advantageous due to flexible operation but also more expensive. The general results refer to the installation with two pumps.

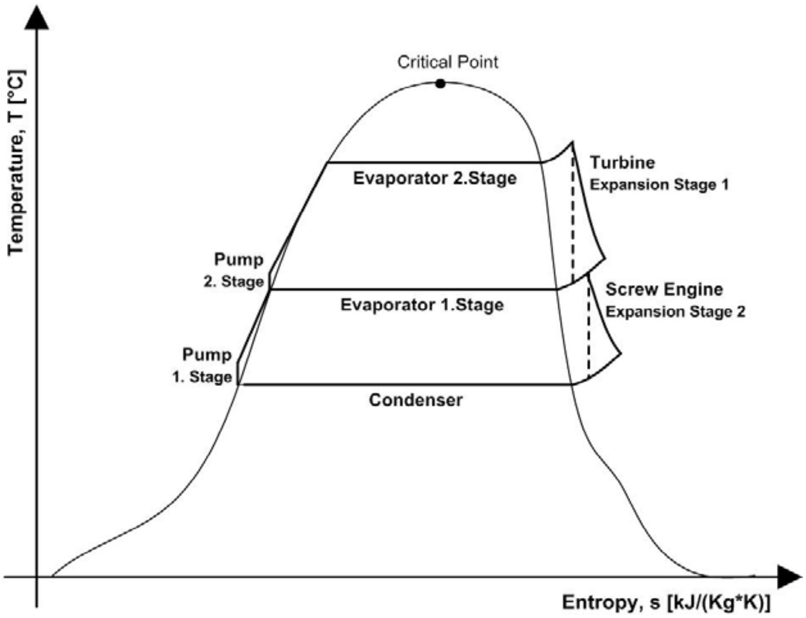


Fig. 3: Simplified view of the two-stage ORC process in the form of a T-s diagram

This simplified view takes into consideration the slight superheating of the working fluid in the first high pressure stage and the energy losses in both expansion stages (i.e. the internal efficiency of the micro-turbine and the screw engine). The influence of these two factors and the condensation pressure is the subject-matter of the following thermodynamic and operational analysis.

3. DESIGN OF THE REFERENCE SYSTEM

This section presents the design of the reference system, which provides the basic starting point for subsequent analysis and generalisations. After practical considerations and application of criteria that are not described here in any further detail, the choice of working fluid fell on R245–fa (Pentafluoropropane), the properties of which are generally known and match the requirements of the prototype installation to be designed and constructed.

Taking into consideration the technical conditions and other aspects associated with realisation of a prototype, the reference system was designed with regard to its thermodynamic and flow characteristics. The thermodynamic specifications of the design are shown in Fig.4.

The variant shown in this graph corresponds to the system with one pump downstream from the condenser, and a pressure reduction stage leading to the low-temperature circuit. (The work of the pump is here left out.)

A representative state of the ORC system with two pumps was chosen for fig. 5, one where the properties and the operational parameters can be understood by means of an example. The pump work was here simplified and assumed to be isentropic, like shown in Fig. 3.

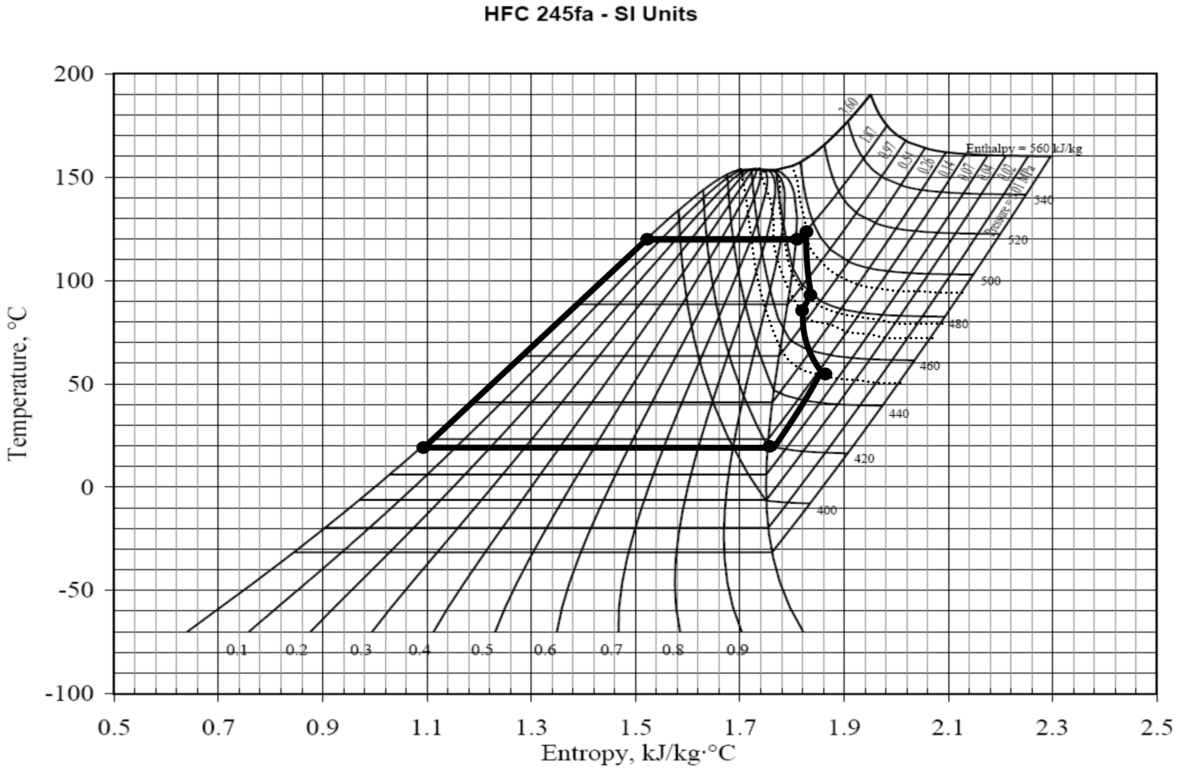


Fig. 4: Design parameters of the reference system

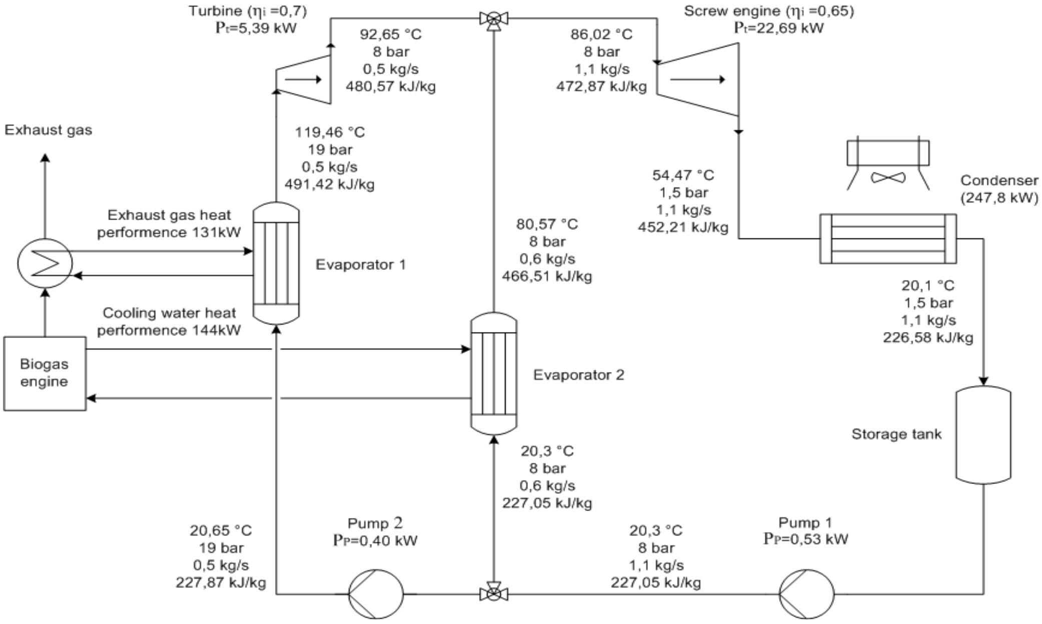


Fig. 5: Representative operational state of the ORC system

In the course of further studies, it was found that a variant with two pump stages provides a number of operational benefits. Both variants were subjected to thermodynamic analysis.

4. CALCULATION PROCEDURE

A special program which is partly based on experience gathered by other researchers [e.g. 6, 7, 8, 9, 13, 14], is rather universal and which also matches the special requirements of the proposed concept was developed in order to conduct extensive arithmetic simulation, analysis and optimisation of the reference system [15]. The program consists of a database mainly containing the properties of different media, and a calculation and optimisation algorithm providing a range of options and possibilities as shown schematically in Fig. 6.

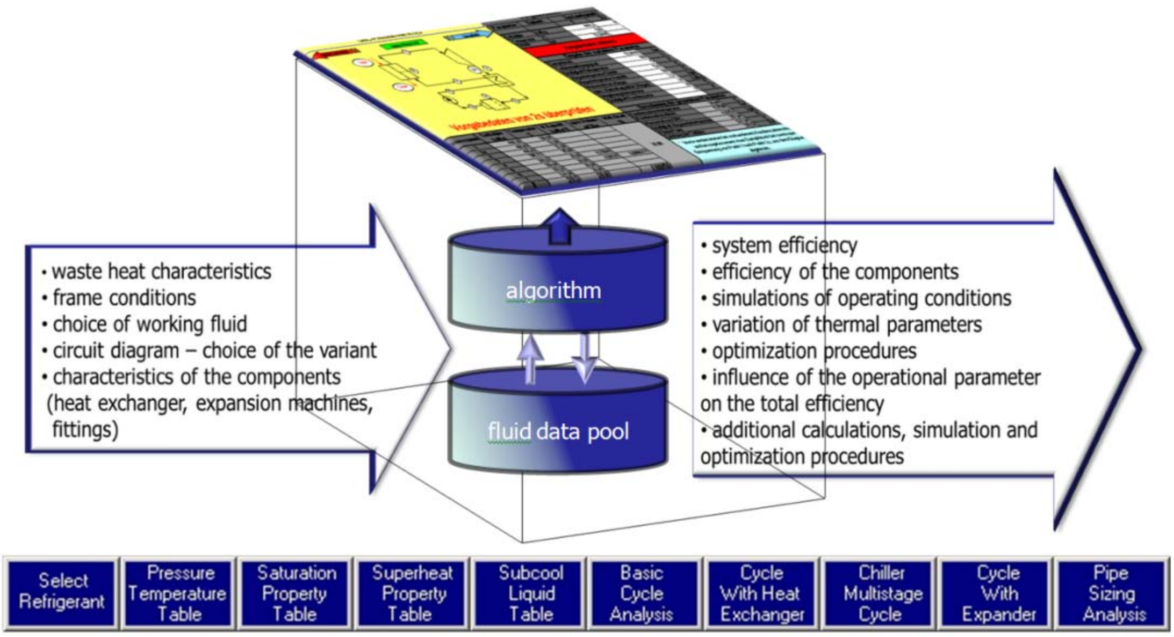


Fig. 6: Schematic diagram of the calculation program and main menu

The calculation algorithm contains different switch variants (one- and two-stage, with and without regeneration) and permits simulation of the process for broad ranges of thermal parameters of the working fluid, and of the parameters of the available heat sources.

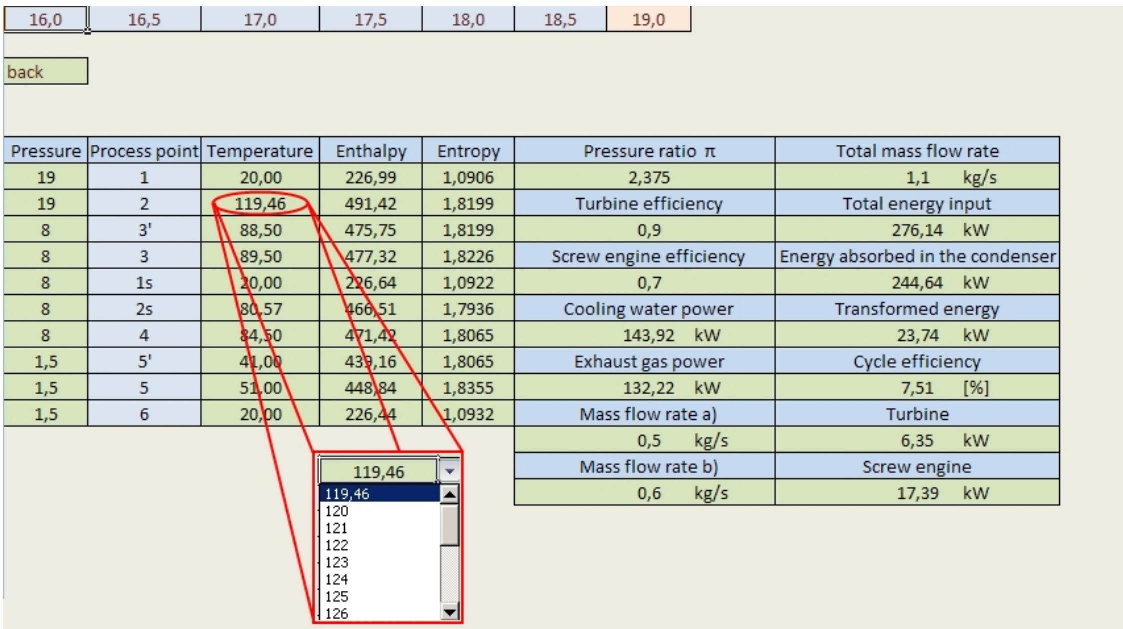
A large database containing the material properties of the working fluids is based on known media whose properties are generally available. In the course of the work carried out, no research on media (either theoretical or practical) was conducted, but the results of research work in this field [e.g. 16, 17, 18] flowed into the optimisation measures being studied, of course.

The calculation method can also be applied in combination with a program for simulating the utilisation of exhaust heat from combustion engines [1]. In this way, it is possible to optimise the adaptation of the ORC process to the available heat source under both steady and quasi-steady operating conditions. In the quasi-steady method, operation of the engine under partial load conditions is simulated arithmetically in such a way that dynamic processes can also be taken into account. The ORC program enables only the simulation of steady operating conditions.

In the following the main components of the ORC calculation program (i.e. the determination of the material properties, as well as the statistical or quasi-statistical calculation procedures) will be illustrated by means of choosing exemplary procedures.

The database was developed using among other sources software offered by the fluid manufacturer, Honeywell Industries [19]. In this software different refrigerants, reference points and measurement units can be selected. The data obtained with this program (as well as data from other available sources) were exported to Microsoft Office Excel, where the entire database was set up.

The operation of the database will be exemplarily explained by means of the turbine inlet parameters. To test for example the influence of the overheating on the process efficiency the turbine inlet temperature can be changed in incremental steps of 1K as it is shown in Fig. 7. ,which apply for R 245fa (chosen saturation point 119.46 °C for 1.9 MPa).



16,0	16,5	17,0	17,5	18,0	18,5	19,0

back

Pressure	Process point	Temperature	Enthalpy	Entropy
19	1	20,00	226,99	1,0906
19	2	119,46	491,42	1,8199
8	3'	88,50	475,75	1,8199
8	3	89,50	477,32	1,8226
8	1s	20,00	226,64	1,0922
8	2s	80,57	466,51	1,7936
8	4	84,50	471,42	1,8065
1,5	5'	41,00	439,16	1,8065
1,5	5	51,00	448,84	1,8355
1,5	6	20,00	226,44	1,0932

Pressure ratio π	Total mass flow rate
2,375	1,1 kg/s
Turbine efficiency	Total energy input
0,9	276,14 kW
Screw engine efficiency	Energy absorbed in the condenser
0,7	244,64 kW
Cooling water power	Transformed energy
143,92 kW	23,74 kW
Exhaust gas power	Cycle efficiency
132,22 kW	7,51 [%]
Mass flow rate a)	Turbine
0,5 kg/s	6,35 kW
Mass flow rate b)	Screw engine
0,6 kg/s	17,39 kW

Fig. 7: The dropdown menu

For user-defined temperature in the overheated area the enthalpy h, entropy s and other values will be automatically updated from the database with a matching procedure, which is represented in Fig. 8.

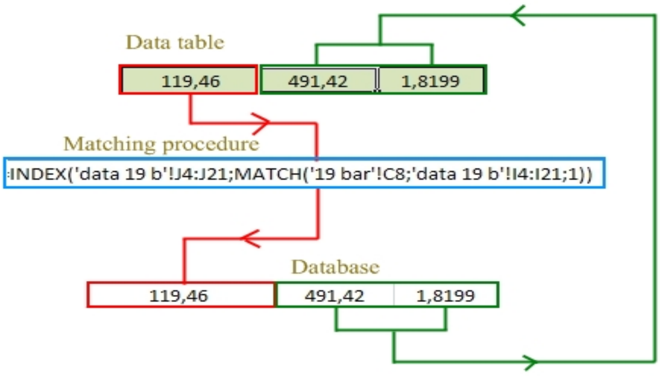


Fig. 8: The matching procedure for different variables

In a similar way all thermal parameters can be determined at all points of the whole process. The state behind the turbine is determined on the basis of the efficiency and with the help of the characteristic curves (efficiency of part load operation) of the respective expansion machine.

The main challenge connected to the thermal calculations of the installation is the dimensioning or subsequent calculating of the heat exchangers under the framing conditions set by the process. Here this difficulty is being illustrated by the example of the evaporator. Fig. 9 shows the temperature conditions in the heat exchanger concerned, consisting of preheating and evaporating parts.

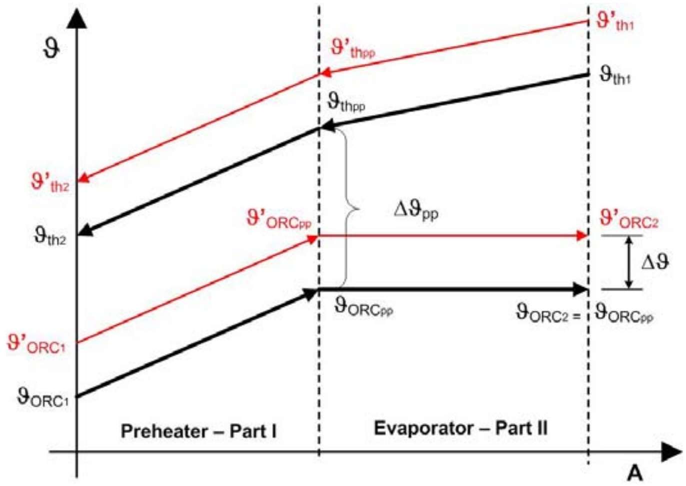


Fig. 9: Temperature characteristics and letter symbols for evaporator

For the preheating part, there holds:

$$\left(\vartheta_{th_{PP}} - \vartheta_{th_2}\right) = \frac{\dot{m}_{ORC}}{\dot{m}_{th}} \cdot \frac{\left(h_{ORC_{PP}} - h_{ORC_1}\right)}{c_{p_{th}}\Big|_{\vartheta_{th_2}}^{\vartheta_{thPP}} \cdot \varepsilon_I} \tag{1}$$

with the performance parameter of the preheater:

$$\varepsilon_I = \frac{1 - e^{\left(-\frac{k_I \cdot A_I}{\dot{W}_{ORC_I}} \cdot \left(1 - \frac{\dot{W}_{ORC_I}}{\dot{W}_{thI}}\right)\right)}}{1 - \frac{\dot{W}_{ORC_I}}{\dot{W}_{Th_I}} e^{\left(-\frac{k_I \cdot A_I}{\dot{W}_{ORC_I}} \cdot \left(1 - \frac{\dot{W}_{ORC_I}}{\dot{W}_{th_I}}\right)\right)}} \tag{2}$$

And for the evaporator accordingly:

$$\left(\vartheta_{th_1} - \vartheta_{th_{PP}}\right) = \frac{\dot{m}_{ORC}}{\dot{m}_{th}} \cdot \frac{\left(h_{ORC_2} - h_{ORC_{PP}}\right)}{c_{p_{th}}\Big|_{\vartheta_{th1}}^{\vartheta_{thPP}} \cdot \varepsilon_{II}} \tag{3}$$

and:

$$\varepsilon_{II} = 1 - e^{\left(-\frac{k_{II} \cdot A_{II}}{\dot{W}_{thII}}\right)} \tag{4}$$

Formulas 1 to 4 result in formula 5 for the overall temperature difference of the thermo-oil:

$$\left(\vartheta_{th_1} - \vartheta_{th_2}\right) = \frac{\dot{m}_{ORC}}{\dot{m}_{th}} \cdot \left\{ \frac{\left(h_{ORC_2} - h_{ORC_{PP}}\right)}{\left[1 - e^{\left(-\frac{k_{II} \cdot A_{II}}{\dot{W}_{Th_{II}}}\right)}\right] \cdot c_{p_{Th}}\Big|_{\vartheta_{thPP}}^{\vartheta_{th1}}} + \frac{\left(h_{ORC_{PP}} - h_{ORC_1}\right)}{\left[\frac{1 - e^{\left(-\frac{k_I \cdot A_I}{\dot{W}_{ORC_I}} \cdot \left(1 - \frac{\dot{W}_{ORC_I}}{\dot{W}_{th_I}}\right)\right)}}{1 - \frac{\dot{W}_{ORC_I}}{\dot{W}_{th_I}} e^{\left(-\frac{k_I \cdot A_I}{\dot{W}_{ORC_I}} \cdot \left(1 - \frac{\dot{W}_{ORC_I}}{\dot{W}_{th_I}}\right)\right)}}\right] \cdot c_{p_{th}}\Big|_{\vartheta_{th_2}}^{\vartheta_{th_{PP}}}} \right\} \tag{5}$$

When changing the operating parameters the respective new pressure and the respective shift of the saturation temperature $\Delta\vartheta$ (Fig. 9) are derived from the characteristic curve of the pump, it means the function of pressure – volume flow rate. This way the dimensioning calculations, as well as the operational calculations (part load operation) can be performed when the framing conditions are given.

5. SELECTED CALCULATION RESULTS

Selected results obtained with the aid of the ORC calculation and simulation program developed are presented in the following, mainly in relation to the two-stage concept presented in the previous section.

In the first step, the influence of the internal efficiency of the two expansion machines on the total ORC efficiency was examined. The total ORC system efficiency, defined by the equation 6, first ignores the work performed by the pump or pumps (ORC gross efficiency).

$$\eta_{ORC} = \frac{P_{SE} + P_T}{\dot{Q}_{SHE} + \dot{Q}_{EGHE}} \cdot \tag{6}$$

Fig.10.1 to 10.4 summarise the representative findings that were obtained.

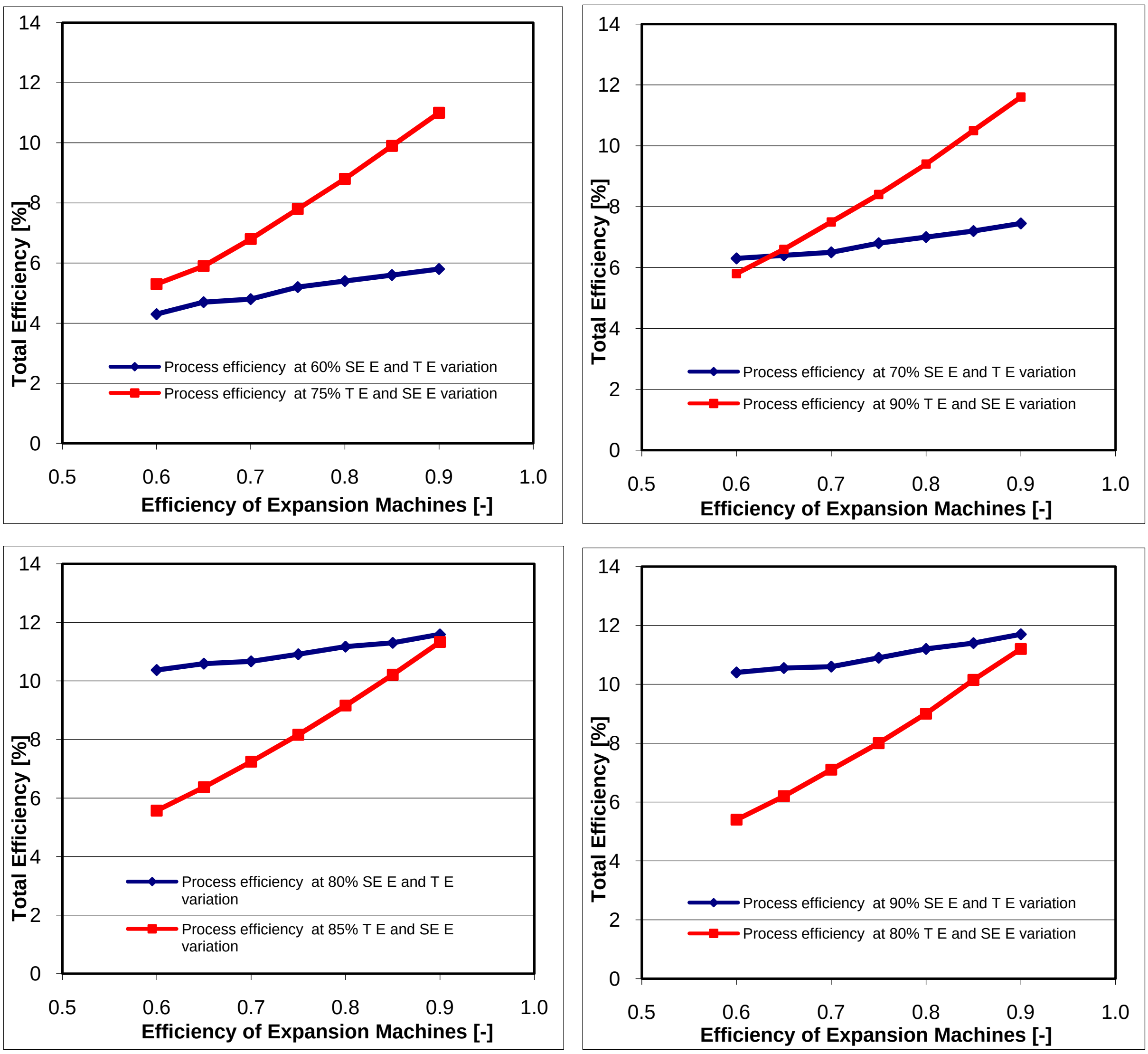


Fig. 10.1-.10.4: Influence of the internal efficiencies of the two expansion machines on the total efficiency of the ORC system. (TE: turbine efficiency, SEE: screw engine efficiency)

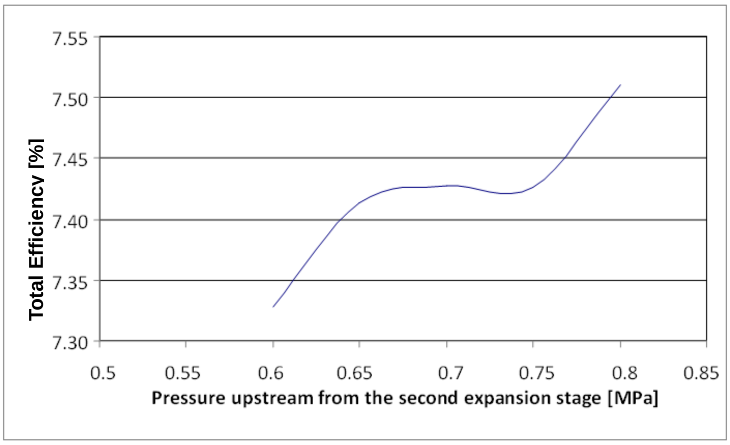


Fig. 11: Influence of intermediate pressure on the total efficiency of the ORC system

In the selected graphs, the total efficiency of the ORC system is shown as a function of the internal efficiency of the respective expansion machine used, with the efficiency of the other expansion machine assumed to be constant. The results were compiled for some variants of these constant initial values for the aforementioned efficiencies of the expansion machines (Figs. 10.1 to 10.4).

In general terms, one can see from the gradients of the curves that the influence of the low-pressure stage is much greater than that of the high-pressure stage.

The selection of the intermediate pressure is also related to this fact. Fig. 11 shows the influence exerted on the total ORC efficiency by the pressure upstream from the second expansion stage, based on the design parameters of the reference system, with the range of pressure variation corresponding to the options for technical realisation.

The intermediate pressure impacts first of all the internal efficiencies of both expansion machines and the resulting load sharing. It can be seen from the curve that the influence observed is relatively small in the parameter range that is technically feasible. Of course, this statement is specific to this special concept and is dependent on the design parameters. In the special case of the planned test bench the optimization possibility related to the choice of an intermediate pressure is marginal at the realistic pressure ratio ranges in both machines.

A standard question concerns the influence of the condenser pressure on the ORC system efficiency, as illustrated in the graph (Fig. 12) for different pressures in the first evaporation stage.

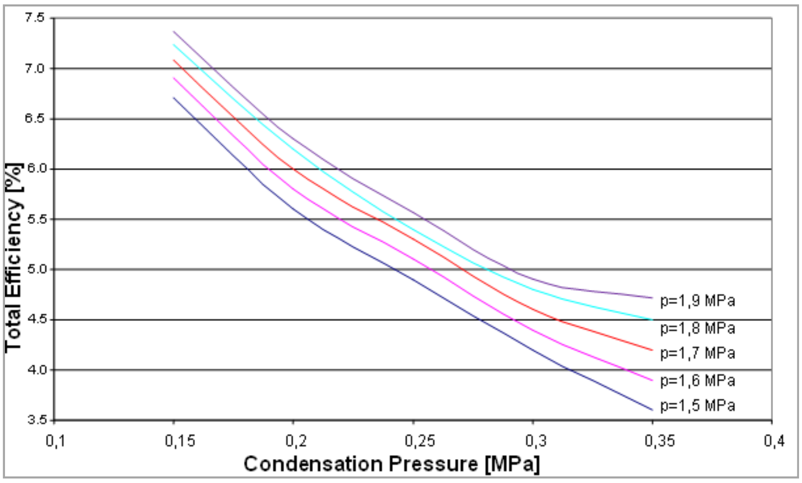


Fig. 12: Change in total efficiency in relation to the pressure in the condenser

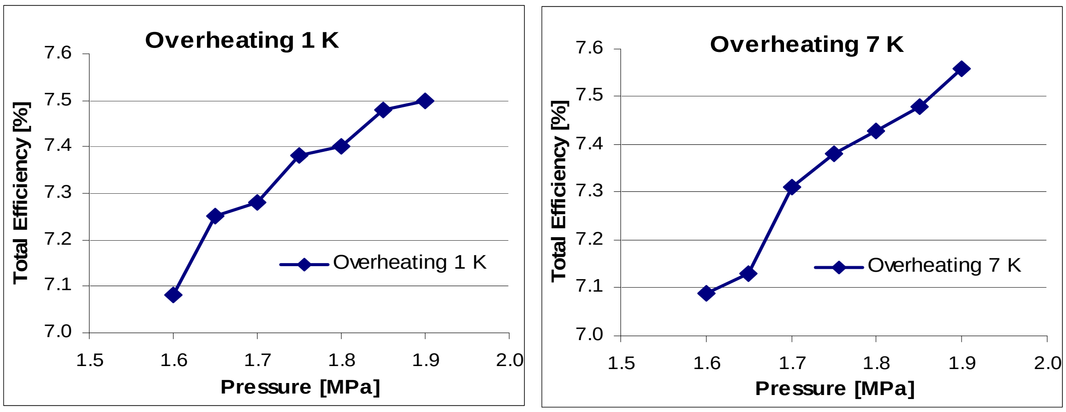


Fig. 13: Total efficiency of the ORC system as a function of initial pressure, for two different levels of vapour superheating (1 K and 7 K)

As expected, lowering the condensation pressure (mainly achieved by reducing the temperature difference in the condenser) provides substantial optimisation potential. The irregularities found in the individual graphs result primarily from inaccuracies in determining the material properties, and from other sources of inaccuracy in the calculation method.

The influence of the initial pressure and of the level of superheating is relatively small, as can be seen from Fig. 13. Here, too, the irregularities in the curves are the result of inaccuracies in programming the characteristic values for the working fluids being used.

This problem has a general impact on the accuracy of calculations. Depending on source, the material properties can be entered with a certain degree of precision, and the effects are particularly apparent in the range where two parameters pressure and temperature can vary, i.e. in the region of the superheated vapour. To illustrate this inaccuracy, the irregular curves and hence the errors resulting from erroneous calculation of the material properties are shown in Fig. 14. In this graph, the total efficiency is plotted as a function of the saturation pressure for different slight superheating of the vapour. It can be seen from the graph that the inaccuracies in determining the material properties has an effect on the total result precisely in the area of the slightly superheated vapour.

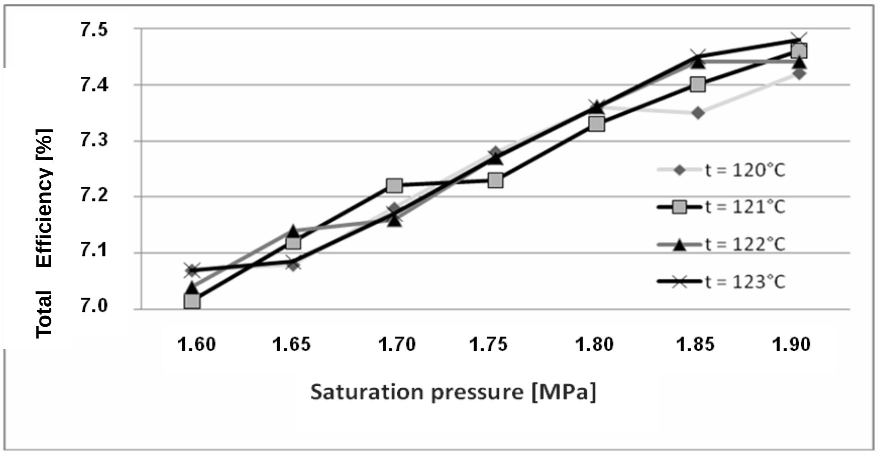


Fig. 14: Efficiency of the ORC process as a function of pressure, for different temperatures of the slightly superheated vapour (influence exerted on the obtained curves by inaccuracies in determining the material properties of the working fluid)

However, with a more exact error propagation analysis it is possible to prove that the resultant errors are within a range that is acceptable for the technical calculations, since it amounts to less than one per cent. Increasing the level of accuracy would require data sources that provide more precise details of the material properties.

The results presented in this section are intended to show, by way of example, the possibilities of the software developed, specifically in relation to the planned demonstration installation and the chosen working fluid. One important optimisation measure that has not been discussed here involves adapting the parameters of the ORC system to the characteristics and temperature level of the available heat source.

The improvement of the efficiency of the biogas plant with an ORC system was investigated by means of a special calculation procedure [20]. The waste heat used by an ORC system of a real biogas plant with 360 kW electrical power was simulated and the calculated improvement of the efficiency of the biogas plant constituted 3.4% (percentage points) at η_{ORC} = 0.06 up to 4.0% (percentage points) at η_{ORC} = 0.07. (The efficiency of the biogas plant without an ORC system amounted to 40.3 %).

It should be highlighted that the ORC system calculation procedure presented does not consider the pump work, but the calculations of the biogas installation with an ORC system consider the ORC pumps as part of the general auxiliary power of the installation as a whole.

6. CONCLUSIONS AND OUTLOOK

In the course of the work carried out, a calculation method and software were developed with which it was possible to analyse the two-stage system concept being presented. The interaction of basic parameters and properties was investigated. The program and its procedures (including the database) are not limited solely to the novel concept, but are suitable in general for theoretical analysis of ORC processes.

On the basis of the design parameters for the envisaged prototype installation, numerous simulations were carried out to investigate the complex interrelationships and influences at work. The influences of the thermal parameters in the key elements of the process and of the characteristics of the two expansion stages on the efficiency of the ORC system were analysed.

The special, innovative feature of the concept consists in adapting the principle to the characteristics of most biogas plants, i.e. two-stage heat input at different temperature levels. Simulation and optimisation of the interaction between the biogas plant and the ORC system is also being integrated in the program developed. With the present database of material properties, it is also possible to analyse the working fluids and their efficiency for the specific applications in question.

Another step will involve a practical analysis of the concept presented, e.g. the options regarding different expansion machines (particularly screw engines), regulation concepts, real losses, and other aspects. A demonstration installation in the form of a test bed has been designed and is currently being realised.

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