MODELLING OF COMMERCIAL BIOMASS-FIRED ORC SYSTEM USING EBSILON PROFESSIONAL® SOFTWARE

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ABSTRACT

This paper demonstrates the use of the commercial software Ebsilon® Professional for modelling and diagnostics of an industrial scale biomass-fired cogeneration system with ORC technology. The software is a commercial object-oriented simulator of thermodynamic systems. It is capable of modelling of complex energy conversion systems under design and off-design conditions. The model consists of a system of individual components described with relevant equations of built-in operational characteristics, which can be modified by the user. Detailed model of the real ORC cogeneration plant in Krosno (Poland) with the Turboden T14 CHP Split ORC unit and the VAS biomass boiler has been built. The model has been calibrated with the plant measurement data obtained from the SCADA system. Then a sample analysis of plant's performance under variable operational conditions such as biomass humidity, thermal oil temperature, network water temperature, etc. has been performed. Examples of off-design characteristics of the system resulting from the model have been depicted in the paper. Parameters such as power output, heat to power ratio, power generation efficiency and overall efficiency have been shown as functions of the selected input variables.

1. INTRODUCTION

Organic Rankine Cycle (ORC) technology is nowadays very popular option for utilization of locally available biomass resources in municipal district heating systems. Investment projects in this field are usually supported by different financial mechanisms. However, legal regulations nowadays frequently change within equipment lifetime. It has significant impact on project economics in countries like Poland, where the intensity of the support has not been so far guaranteed. It has been presented by Kalina et al. (2019) that under current market conditions economic performance indices of investment project vary within its operational phase and can't be determined at the stage of investment decisions. There are correction actions required (Rettig et al., 2017) and therefore plant owners and operators should be supported by effective tools that would provide credible information for making decisions on changes. Another issue, which is especially important in case of ORC systems is monitoring of technical condition of production assets (Salogni et al., 2017).

Operational diagnostics and optimisation of biomass-fired cogeneration plants can be nowadays provided by a tailored set of hardware and software tools, which can be called an Expert Systems (ES). Such system can be created using commercial software such as the SR::EPOS of STEAG Energy Services GmbH (Spliessgardt et al., 2015), universal software such as MATLAB (Jakoubek et al., 2010) and Dymola (Rettig et al., 2017) or can be built programmatically in any programming language, which is the most time consuming and costly approach.

In recent years many papers have been published on theoretical and experimental performance of the ORC technology. However, according to Liu et al. (2018) there is lack of available information regarding real ORC units on industrial level. According to Park et al. (2018) there is a large gap between research and development for source and sink temperature differences above 150°C, and the majority of published experimental works were performed for micro- and mini-scale ORC systems. Moreover, there are not many paper presenting modelling of ORC systems using commercial software widely used at engineering design companies.

This paper presents model for operation planning and diagnostics of existing biomass-fired cogeneration system with the Turboden T14−CHP SPLIT ORC unit. The model has been developed using Ebsilon® Professional software (STEAG Energy Services, 2019). This is object-oriented software for simulation of thermodynamic processes in energy conversion plants (Madejski et al., 2017). Javanshir et al. (2017) have used this software for extensive techno-economic analysis of exhaust heat recovery from the Brayton and steam Rankine cycles and its use in a simple ORC. Another example of the use of Ebsilon® Professional software for advanced study of an ORC system is the work presented by Dubberke et al. (2015).

In this work, the model of complex system, which consists of biomass combustion system, thermal oil circuit and the ORC unit has been built. It takes into account both the nominal (design) parameters of system components as well as it enables estimation of plant's performance during operation in real, variable conditions (off-design conditions). Functionality of the model is discussed on example of the cogeneration system in Krosno (Poland). The model identifies optimal operational parameters for given load and ambient conditions. If integrated with plant's SCADA system, the model can constitute an effective diagnostics tool within the SR::EPOS environment. In this paper there has been presented structure of the model and results of simulations, which indicate key performance parameters of the system. There has been also examined system sensitivity to operating conditions. It should be however emphasised that the paper is focused on the software tool rather than on a detailed analysis of the ORC system. The detailed discussion of the Krosno system performance has been given in our recent papers (Kalina, Świerzewski, Strzałka, 2019; Kalina, Świerzewski, 2019).

2. ORC COGENERATION PLANT DESCRIPTION

The system modelled in this work consists of the biomass-fired thermal oil boiler manufactured by VAS and the Turboden T14−CHP SPLIT ORC unit of 1317 kW electric power output. The ORC working fluid is octamethyltrisiloxane $C_8H_{24}Si_3O_2$ (short name: MDM, CAS No. 107-51-7). The fuel is biomass in the form of wood chips. The heat between biomass combustion system and the ORC unit is transferred by the Therminol 66 thermal oil. Main technical data of the plant are given in Table 1.

Table 1: Design specification of CHP unit in Krosno according to Turboden

Quantity	Unit	Value
Generator power output	kW_e	1317
Captive power consumption	kW_e	62
Indicative turbine isentropic efficiency	%	up to 90
Heating network water temperature (in/out)	°C	60/80
Thermal output to water circuit	kW_{th}	5341
Thermal output from gas condensation system	kW_{th}	800
Thermal output from water cooled moving grate	kW_{th}	120
Total cogeneration heat output	kW_{th}	6270
Nominal temperature HT oil loop (in/out)	°C	310/250
Thermal power input HT loop	kW_{th}	6130
Nominal temperature LT oil loop (in/out)	°C	250/130
Thermal power input LT loop	kW_{th}	585
Overall thermal input	kW_{th}	6715
Indicative biomass consumption (50 % water content)	kg/h	2935
Gross electric energy efficiency	%	19.6
Biomass boiler efficiency	%	87

Schematic diagram of the cogeneration process is depicted in Fig. 1. The system runs under variable conditions concerning heating load, heating grid temperature and biomass composition. Wet biomass in the form of wood chips is delivered to the combustion chamber ***12*** by a piston type conveyor. Combustion air is initially heated by the exhaust gas in the recuperator ***16***. Recirculated exhaust gas EGR is also delivered to the primary and secondary zones of the combustion chamber. Heat from the combustion section is transferred to the thermal oil in high temperature (HT) main spiral type heat exchanger ***13***, high temperature economiser ***14*** and low temperature (LT) economiser ***15***. High temperature thermal oil circuit integrates the HT combustion gas – thermal oil heat exchangers with MDM evaporator ***3*** and the heater ***2*** of the ORC unit**.** The LT thermal oil circuit delivers heat to the SPLIT heat exchanger ***1***. Important elements of the thermal oil circuits are ORC three-way admission valves ***17*** and ***18*** that control the flow of Therminol 66 into the ORC heat exchangers. The working fluid leaves the evaporator slightly superheated and goes through the inlet valve ***5*** to the turbine ***6***, and then to the hot side of the regenerative heat exchanger ***8***. The turbine drives electric generator ***7***. From regenerator ***8*** hot side outlet MDM goes into the condenser ***9***, then through the filter ***10*** to the main cycle pump ***11***. After the pump the flow of working fluid is split into two streams, one directed to the cold side of the regenerative heat exchanger and one that goes to the SPLIT unit. In the ORC condenser the network water is heated from return to forward temperature. The flow of working fluid within the cycle in not measured. The measured flows are thermal oil flows $\dot{m}_{1OIL}$ and $\dot{m}_{1OIL}$ respectively as well as the flow of condenser cooling water.

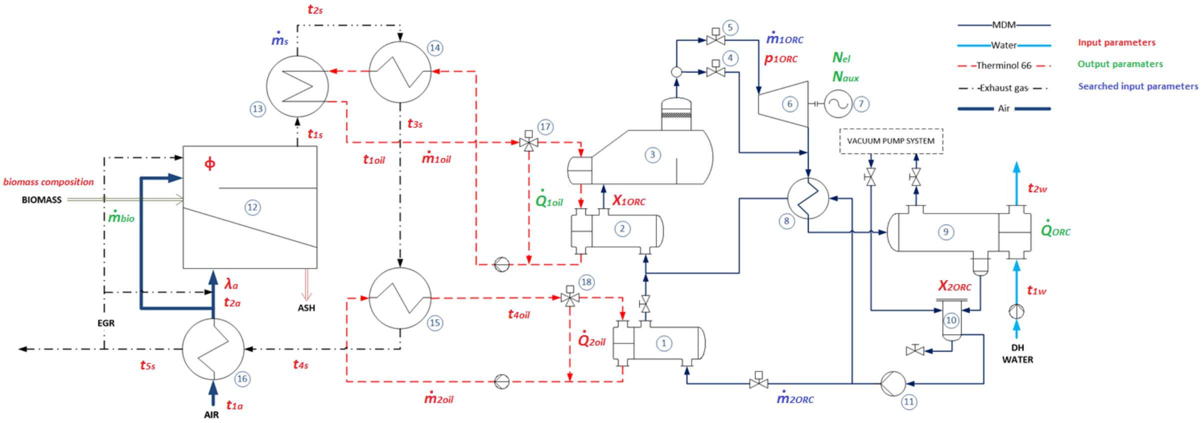

Figure 1: Simplified diagram of biomass fired ORC cogeneration system in Krosno (1 – SPLIT heat exchanger/MDM preheater; 2 – MDM heater; 3 – MDM evaporator; 4 turbine by-pass valve; 5 – turbine inlet valve; 6 – turbine; 7 – electric generator; 8 – working fluid regenerative heat exchanger; 9 – MDM condenser/DH network water heater; 10 – filter; 11 – pump; 12 – biomass combustion chamber; 13 – spiral type thermal oil heater; 14 – high temperature economiser; 15 - low temperature economiser; 16 – recuperator/combustion air heater; 17, 18 – thermal oil three-way admission valves; EGR – exhaust has recirculation)

Wood chips are of variable properties in terms of composition, heating value, moisture content and ash content. In the Krosno plant these parameters are measured periodically. Several samples of fuel are collected within each month and subsequently a monthly average value of each parameter is determined. Results have been depicted in Fig. 2. These measurements have been adopted as model input values.

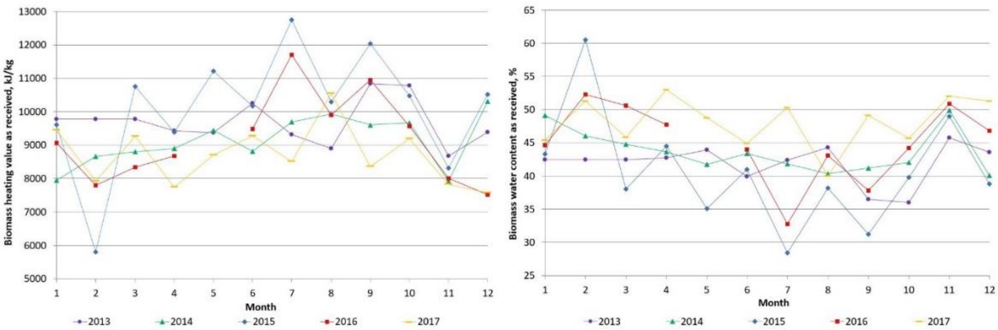

Figure 2: Biomass heating value and water content at Krosno plant

3. MODEL STRUCTURE AND FUNCTIONALITY

The EBSILON® Professional model of the CHP system has been depicted in Fig. 3. The model consists of a system of individual components, which are described by equations of thermodynamic processes as well as mass and energy balances. It has been built using predefined components provided within the software, which were dragged from the library and dropped into the flowsheet diagram. All the existing physical components, which are depicted in Fig. 1, have been represented with relevant EBSILON blocks of the model. These are: combustion chamber, exhaust gas heat exchangers, thermal oil circuit heat exchangers, working fluid heat exchangers, ORC turbine and heating network. In the first step the model was generated in the reference state (design mode) and calibrated using the technical specification of the system given in Table 1. In the off-design mode EBSILON simulates operational parameters of the system for new input parameters and given results of design calculations. In the off-design mode all the design parameters of the system remain fixed, while the actual operating parameters under variable input signals are determined using scaling rules (off-design characteristics). Key components have been provided with relevant equations of user modified operational characteristics derived from the correlating measurement data. The simulation model was calibrated using real measurement data acquired from the SCADA system of the plant. Historical measurement data, which were collected within the GE Historian database server of the plant's SCADA system, allowed identification of the system and elaboration of realistic operational characteristics of individual model components (Kalina et al., 2018). Model input parameters, which control the model, and output variables are presented in Table 2 and also depicted in Fig. 1.

Table 2. Input and output parameters in the model

Physical quantity	Unit	Value or range
Fixed input values		
Ambient air temperature – $\boldsymbol{t_{1a}}$	°C	25
Air temperature to combustion – $\boldsymbol{t_{2a}}$	°C	140
Air ratio – $\boldsymbol{\lambda_a}$	-	1.4
Exhaust gas temperature at combustion chamber outlet– $\boldsymbol{t_{1s}}$	°C	970
Exhaust gas temperature after heat exchangers – $\boldsymbol{t_{2s}, t_{3s}, t_{4s}}$	°C	370/220/185
Thermal oil flow (high temperature loop) – $\boldsymbol{\dot{m}_{1oil}}$	kg/s	30.6
Thermal oil flow (low temperature loop) – $\boldsymbol{\dot{m}_{2oil}}$	kg/s	1.48
Vapor quality of working fluid at evaporator inlet – $\boldsymbol{X_{1ORC}}$	-	0
Vapor quality of working fluid at condenser outlet – $\boldsymbol{X_{2ORC}}$	-	0
Searched input parameters		
Exhaust flow – $\dot{\mathbf{m}}_{\mathbf{s}}$	kg/s	-
Working fluid flow goes to turbine – $\boldsymbol{\dot{m}_{1ORC}}$	kg/s	-
Working fluid flow goes to split system – $\boldsymbol{\dot{m}_{2ORC}}$	kg/s	-
Values varied in sensitivity analysis		
Biomass moisture content – $\mathbf{w}$	%wt	0.3 – 0.5
Thermal oil temperature at ORC evaporator – $\boldsymbol{t_{1oil}}$	°C	200 – 310
Thermal oil temperature at split heat exchanger – $\boldsymbol{t_{4oil}}$	°C	140 – 220
Thermal oil power input (split loop) – $\boldsymbol{\dot{Q}_{2oil}}$	kW_{th}	0 – 475
Thermal load of combustion chamber –ϕ	%	0.3 – 1.0
Pressure of working fluid at ORC evaporator – p_{1ORC}	bar	3 – 10,6
Heating network temperature, return/forward – $\boldsymbol{t_{1w}, t_{2w}}$	%	30 – 60/65 – 110
Output parameters		
Generator power output – $\boldsymbol{N_{el}}$	kW_e	200 – 1400
Captive power consumption – $\boldsymbol{N_{aux}}$	kW_e	11 – 56
ORC condenser heat output – $\boldsymbol{\dot{Q}_{ORC}}$	kW_{th}	1100 – 4200
Thermal oil heat input (high temperature loop) – $\boldsymbol{\dot{Q}_{1oil}}$	kW_{th}	1400 – 6150
Biomass consumption – $\boldsymbol{\dot{m}_{bio}}$	kg/h	700 – 2300

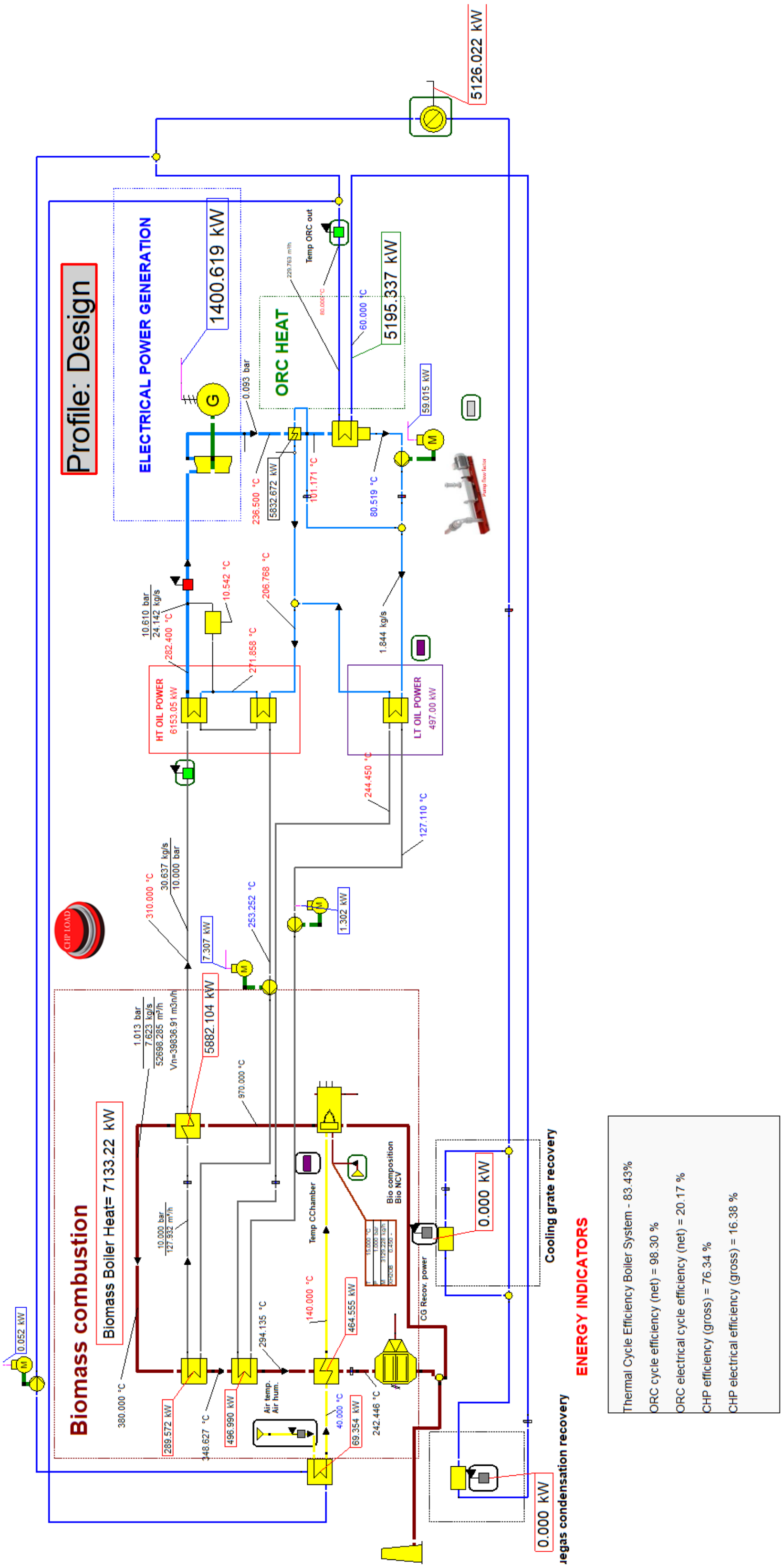

Figure 3: Ebsilon® Professional model of the biomass-fired plant with Turboden T14−CHP ORC unit

There have been distinguished two types of user-defined control parameters: explicit input parameters, which represent measured values within the SCADA system, and implicit input parameters, which aren't measured values and must be searched by the model. The model simulation required determination of the unknown flow of exhaust gas from the load-dependent combustion chamber as well as the flow of working fluid in the ORC module. To determine the missing measurement data, the "controller" component of the EBSILON® Professional was used as depicted in Fig. 4. The procedure was based on the iterative determination of the missing values until the absolute value of the difference between the generator power value from the model and the measured value was at minimum.

The model has been validated against measurement data collected over one year of operation. Quality of the simulation model has been assessed by calculating the relative error $\delta_{x,i}$ of selected parameters:

$$\delta_{x,i} = \left(\frac{x_i^{model} - x_i^{mesured}}{x_i^{measured}}\right) \tag{1}$$

Where: x_i^{model} – simulation model value in the i-th calculation step, $x_i^{measured}$ – reference (measured) value in the i-th calculation step.

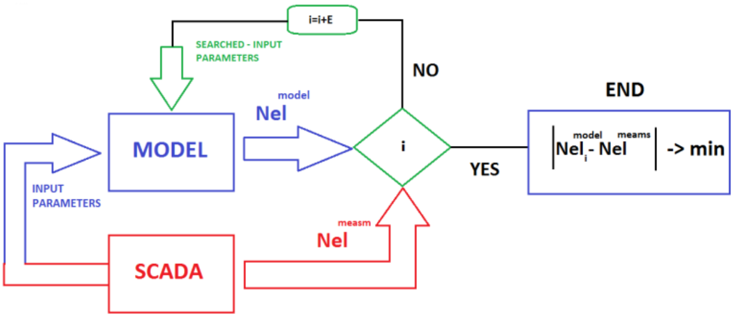

Figure 4: Block diagram of the “controller” component operation

The relative errors of generator power output at different load have been presented in Table 3.

Table 3. Examples comparison of generator power output in different cogeneration loads.

Load CHP	Measurement	Model	δx_i
100%	1338 kW	1377 kW	2,91%
90%	1263 kW	1295 kW	2,53%
70%	858 kW	822 kW	4,20%
60%	722 kW	734 kW	1,67%
50%	647 kW	643 kW	0,56%

The revealed the differences between simulated and measured values of generator power from 0.56 to 7.10% and annual average relative error $\overline{\delta}_{x,i}$ of 3.48%. Results of annual system simulation and accuracy of the model have been depicted in Fig. 5.

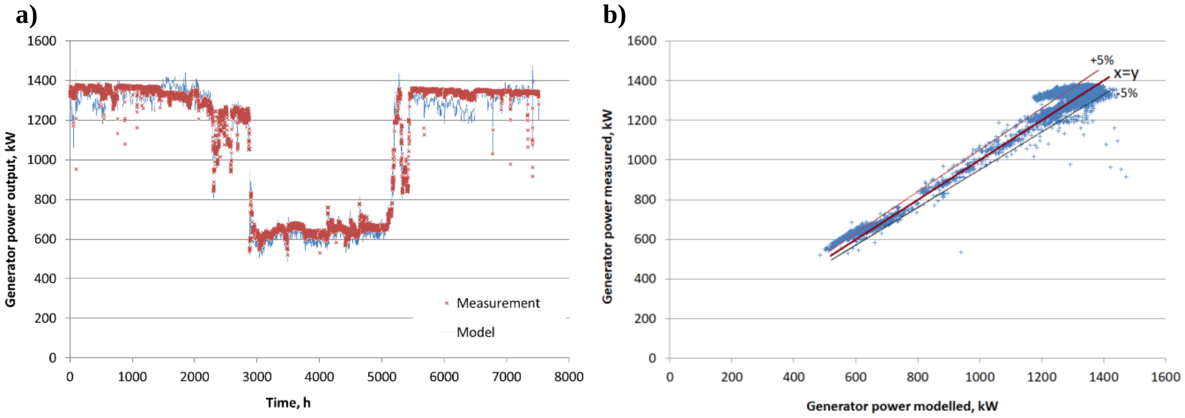

Figure 5: Results of annual system simulation (a) and accuracy of generator power prediction (b)

It has been found that the model is more precise for part load conditions. The main reason for this is thermodynamic state of the ORC working fluid at the outlet of the evaporator. During operation at higher loads (in winter), the MDM is superheated (5-10 K degrees superheating). During summer operation working fluid is close to the saturation point and accuracy of the simulation model is better. However, uncertainties of measured data used in the verification process must be also taken into account.

After the model had been calibrated and validated with measurement data it enabled predictions of the system state parameters determination of optimal decision variables (settings) of the integrated system with ORC CHP and heat only boilers. In this paper the model has been used for analysis of system's sensitivity to key operating parameters. There have been taken into account variability of the following input values: – thermal load of combustion chamber (ϕ), – therminol 66 temperature at the ORC evaporator inlet (t_{1oil}), – district heating network water temperature at the ORC condenser outlet (t_{2w}), – biomass water content (w). These parameters have been identified as the most influencing the performance of the system. Within this exercise remaining parameters have been fixed at nominal values. Sensitivity of the plant to operating conditions has been presented in the form general performance indices such as achievable electric power, biomass to electricity energy conversion efficiency and energy utilisation factor. The gross energy efficiency of the biomass-fired cogeneration plant is:

$$\eta_{el} = \frac{P_{el}}{\dot{m}_{bio} LHV_{bio}} \tag{2}$$

The overall gross efficiency of the system is defined as the energy utilization factor:

$$EUF = \frac{P_{el} + \dot{Q}_{ORC}}{\dot{m}_{bio} LHV_{bio}} \tag{3}$$

Net values of the defined efficiencies consider power consumption for working fluid circulation pump.

4. RESULTS AND DISCUSSION

Results of computer simulations of the biomass-fired ORC system under different thermal load of the biomass boiler are given in Table 4. This set of simulation results has been achieved under assumption of constant combustion excess air coefficient λ, constant values of exhaust gas temperature at particular points of the system and constant condenser inlet and outlet temperature. The mass flow of exhaust gas increases with the flow of fuel. It has been varied until the desired thermal oil temperature at the evaporator inlet has been obtained.

Table 4. Results of computer simulations at different thermal load

Specification parameter	Unit of measure	Value		
		100% load*	70% load*	50% load*
Generator power output	kW	1400.6	1037	626
Captive power consumption	kW	59	35	12
ORC turbine isentropic efficiency	%	77.0	91.1	97
Fuel power input (@45% water content)	kW	7988	6000	3902
Biomass flow (wood chips)	kg/h	2181	1638	1065
Thermal oil temperature at boiler inlet/outlet (HT loop)	°C	253/310	233.5/275	218/245
Thermal oil temperature at boiler inlet/outlet (LT loop)	°C	133/245	1420/226	166/212
Exhaust gas flow	kg/s	7.26	5.25	2.25
Working fluid (MDM) flow to turbine	kg/s	24.14	16.9	10.86
Working fluid (MDM) flow to split system	kg/s	1.76	1.33	0.73
Heating network temperature, return/forward	°C	60/80	60/80	60/80
ORC condenser heat output	kW	5174	3706	2392
Gross electric efficiency of the system	%	17.53	17.57	15.92
Net electric efficiency of the system	%	16.80	16.70	15.74
Cogeneration plant net overall efficiency	%	81.56	79.56	75.99

* The relative load is defined as the actual heat output of the main exhaust-gas-oil exchanger relative to its nominal output

Sample results of simulations are presented in Fig. 6 to 10. Electric power at the generator output and gross energy efficiency of the system have been depicted in Fig. 6a for different values of condenser water outlet temperature t_{2w}. Condenser heat output in this case was fixed at 5200 kW, water inlet temperature was 60°C and thermal oil inlet temperature was 310°C. Results revealed decrease in generator electric power of 11.6 kW/K and efficiency drop of 0.6 percentage points per K (average values). Higher values of power and efficiency deterioration are at lower water outlet temperature as correlations are not linear. In the case condenser water temperatures are 60/80°C but evaporator thermal oil inlet temperature varies from 310°C to 280°C the power output decreases at average by 4.9 kW/K whereas energy efficiency by 0.05 percentage points per K.

Figure 6b depicts dependency of generator power output and gross value of energy efficiency on district heating network water flow through ORC condenser. Inlet and outlet temperatures are 60/80°C and oil inlet temperature is 310°C. The results revealed a decrease of electric power at smaller mass flows of cooling water. However, the relationship is strongly nonlinear and there is a value of water flow at which energy conversion efficiency is at maximum. Moreover, the change in electric power with cooling water from is bigger at small flows. This means that the performance of the real system is substantially influenced by variation of cooling water flow at part load conditions in summer season.

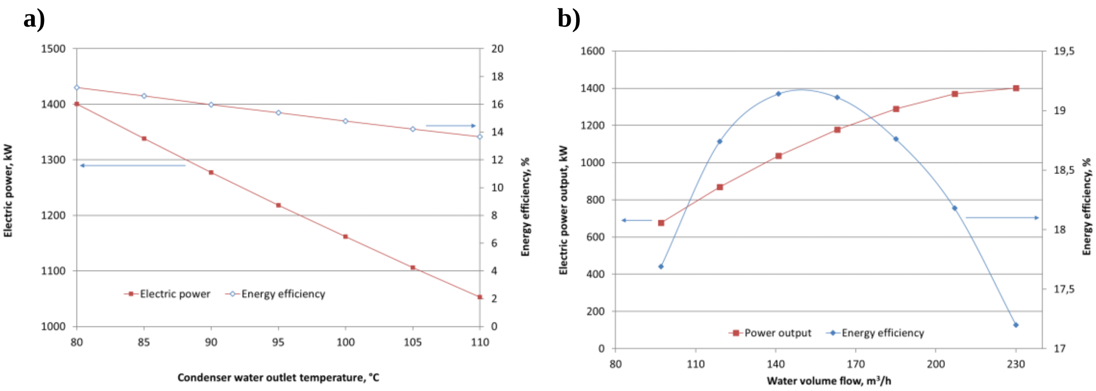

Figure 6: Electric power and energy efficiency as a function of condenser outlet water temperature (a), and condenser cooling water flow (b)

Figure 7 shows relative values of energy efficiency and EUF, which are defined as:

$$\frac{\eta_{el}}{\eta_{el,des}} = \mathrm{f}_1(t_{2w}); \frac{EUF}{EUF_{des}} = \mathrm{f}_2(t_{2w}); \qquad (4)$$

As depicted in Fig. 7 in this case there were also noticed variations of the degree of working fluid superheat. Eventually, it has been concluded that due to strong sensitivity to condenser conditions the stabilization of operating parameters in this area is of critical importance in the context of annual energy and economic performance of the plant.

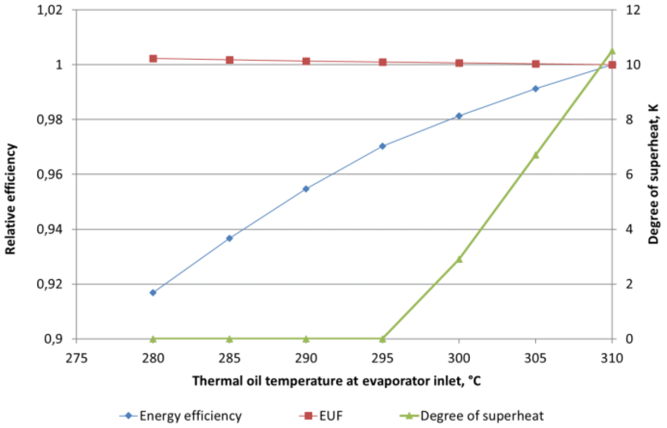

Figure 7: Relative energy efficiency and EUF of the system as a function of thermal oil inlet temperature

Another critical parameter of the system operation is the degree of working fluid superheat above saturation temperature for evaporator pressure. Sample results are depicted in Fig. 8. At higher values of the degree of superheat lower electric power output has been achieved. In the same time gross energy efficiency increases. Therefore, monitoring of this parameter in the real system is also important for final economic results.

Figures 9 and 10 present influence of heating load and biomass water content on performance of the biomass boiler and energy efficiency. The simulation has revealed that the increase of the biomass moisture content from 30% to 50% reduces the efficiency of the boiler by more than 2 percentage points. The corresponding decrease in the gross biomass to electricity conversion efficiency is below 0.5 percentage points.

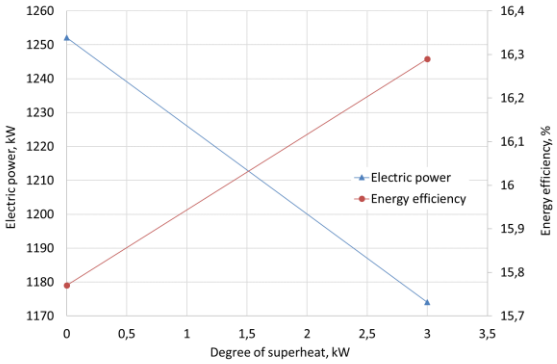

Figure 8: Electric power and efficiency as functions of degree of working fluid superheat

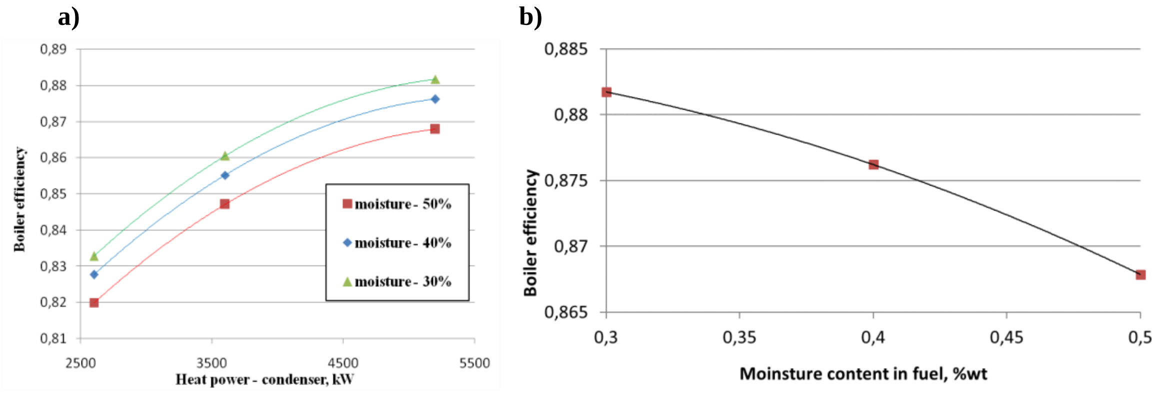

Figure 9: Boiler efficiency as a function of condenser heating output and biomass water content (a), and biomass water content (b)

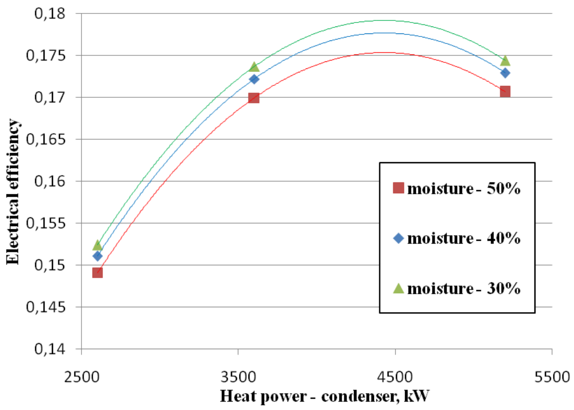

Figure 10: Gross energy conversion efficiency as a function of condenser heating output and moisture content

5. CONCLUSIONS

The paper presents application of the commercial software EBSILON® Professional to support operation of the industrial scale ORC CHP system. The use of computer modelling and simulation allowed examination of key input variables (settings) on system performance. Simulations revealed that sensitivity of the system to the parameters such as load factor, biomass water content and district heating network water temperature is relatively high. The best performance can be achieved for relatively dry biomass at high system load, low condenser outlet temperature and low degree of superheat of the working fluid. The model also allows for fast diagnostics as the modelling results can be compared with measurements at any time, thus the operator could see if there are any critical differences. In this way system malfunctions can be detected earlier. Moreover, computer-aided thermodynamic simulations have also given a possibility for credible determination of decision variables at the stage of planning of changes of system configuration and operational strategy, thus giving the basis for economic analysis. For example, the model was used for sizing of the hot water storage tank for increasing system flexibility and making profits out of selling electric energy on balancing market (Świerzewski M., Kalina J., 2019).

NOMENCLATURE

EUF	energy utilization factor	(-)
LHV	lower heating value	(kJ/kg)
$\dot{m}$	mass flow	(kg/s)
P	power	(kW)
$\dot{Q}$	heating output	(kW)
η	efficiency	(–)

Subscript

el	electric
bio	biomass
des	design

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