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Performance Improvement of Biomass Cogeneration Plant by Dual Loop Organic Rankine Cycle

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Biomass cogeneration plants in wood industry are usually designed to cover large share of site heat demand. However, plant capability to cover peak load in winter could lead to low utilisation of installed capacities at sites whit high seasonal heat demand fluctuations. At some sites, where income of sold electricity is essential for plant investment payback, non-cogeneration operation mode is applied and evacuation of surplus heat through air cooled heat exchangers is usual practice. Price increase of wood chips, as a consequence of increased demand, accompanied by implementation of sustainability criteria for biomass utilisation forced plant owners to reconsider existing business model and to find more efficient ways of biomass utilisation.

Based on analysis of operational pattern of existing 1 MW organic Rankine cycle plant in wood pellets processing industry in Croatia, configuration and parameters of an additional low temperature organic Rankine cycle have been investigated in order to find technically and economically optimal configuration. Taking into account time dependant variation of surplus heat of the high temperature cycle in the range of 1 to 3 MW and variation of ambient temperature, net output power of the low temperature cycle has been optimised. Off-design and part-load operating conditions have been also considered and results of analyses have been presented.

1. Introduction

Rapid increase in interest for various aspects of organic Rankine cycle (ORC) implementation, particularly in working fluid selection and configuration optimisation could be observed in recent years. As KCORC (2013) announced proportion of engineering papers dealing with ORC in Elsevier publications has grown exponentially since the year 2008. Currently number of research articles and technical reports many times surpasses a number of plants in operation (Quoilin et al., 2013). Since importance of more efficient utilisation of heat and low temperature sources has not been diminished, further and continuous growth of number of plants in operation could be expected especially in countries with favourable regulatory framework.

Alongside with thermo-economic and thermodynamics optimisation issues there are several recent articles focused on part-load aspect of operation. In (Erhart et. al., 2013) results of the analysis of the operation of a heat guided biomass combined heat and power plant connected to district heating system have been shown. Results of research of low temperature ORC applications in connection with fluctuating waste heat source in single cycle arrangement have been presented in (Lecompte et al., 2013) with focus on thermo-economic optimization. In (Ibarra et al., 2014) changes of cycle thermal efficiency in relation to varying working pressures, expander rotation speed and condensation temperatures have been calculated. Performance of dual-loop ORC arrangement has been analysed in (Wang et al., 2012) in recovering exhaust waste heat of gasoline engine, while in (Yang et al., 2014) similar dual-loop scheme has been investigated in connection with diesel engine.

Coupling of two or more ORC systems is expensive in principle, so the application of dual (multiple) loop system is justifiable only at sites where increased system efficiency significantly contributes to covering of additional investment costs (Ho et al., 2012). However, almost forty commissioned systems of one manufacturer at sites with stationary engines, biogas and biomass, solar thermal or geothermal facilities

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(Electratherm, 2014), as well as similar installations of other manufacturers, indicate that ORC system with temperatures of heat source below 100 °C could be viable as second loop in ORC cascade. Based on analysis of operational pattern of existing 1 MW organic Rankine cycle plant in wood pellets processing industry a simplified simulation analysis of yearly operation of second, low temperature ORC plant has been performed and implementation potential has been assessed.

2. ORC cogeneration plant

Following common practice established in Central Europe in last decade, owner of a pellets factory decided to invest in cogeneration plant to assure thermal energy required for belt dryer operation. Compared to utilisation of conventional solutions for providing heat for drying, biomass fired hot gas or hot water boilers, cogeneration plant is more complex and even less efficient solution (in terms of total amount of heat required for evaporation of same amount of water). However, specific boundary conditions defined by favourable regulatory framework for electricity generated in biomass fired cogeneration plants, enable profitable operation. Considered plant comprises thermal oil boiler fired by wood chips and ORC module manufactured by market leader with designed electric output of approximately 1 MW and thermal output of approximately 4 MW. The construction of plant was finished in the second half of the year 2012. After several months of commissioning and controls system tuning a stable plant operation was established.

2.1 Electricity profile

Typical plant operation profile is illustrated for October 2013 in Figure 1. Hourly profile of electricity generation has been presented at the upper graph, while at the lower graph so called parasitic consumption has been shown. Approximately three quarter of required 180 kW is consumed by thermo-oil and silicone oil pumps, air and flue gases fans and by fuel and ash processing system. The rest, up to approximately 40 kW is required by fans of air cooled water cooler. Operation of water cooler is necessary for evacuation of surplus heat, during the time of reduced heat demand, in order to maintain electricity generation at approximately nominal level. Short drops in electricity generation, when plant was temporarily switched off the grid, were caused by local distribution network conditions.

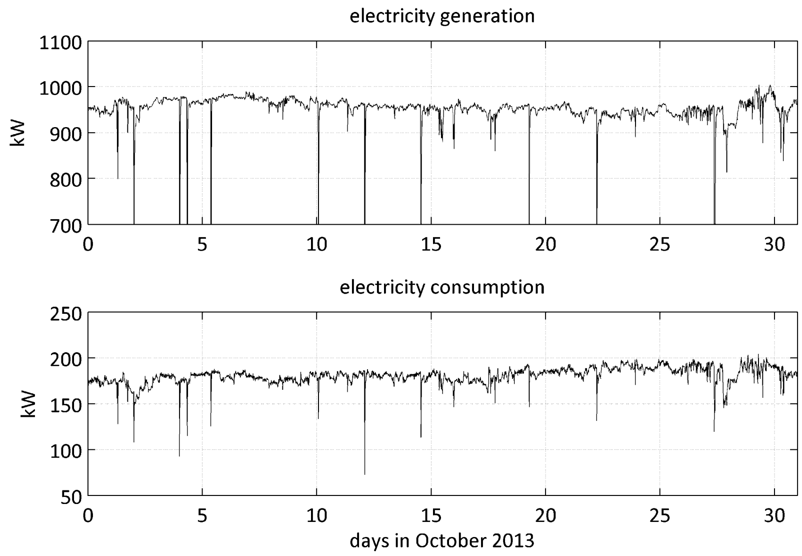

Figure 1: Hourly data on electricity generation and electricity consumption of considered biomass fired cogeneration plant in pellets processing factory in October 2013

2.2 Heat profile

Condenser of the ORC module is cooled by the hot water circuit which is coupled with belt dryer of pellets raw material (sawdust and/or shavings of suitable size). The material is dried up to the about 10 % of moisture content which is required in subsequent stages of pellet processing. Small proportion of hot water heat is utilised seasonally for space heating. Heat consumers (belt dryer, space heating system and additional water cooler) maintain temperatures of the hot water in the 80/60 °C range. Since hourly data on heat demand were not available it was not possible to determine exact amount of surplus heat evacuated by water cooler during the year 2013. An estimate was made in order to determine the amount of available waste heat which could be utilised in low temperature ORC plant.

Results of analysis of yearly heat demand have been presented in Figure 2. Average monthly temperatures have been presented at upper left graph within the range of minimum and maximum values. At upper right bar chart monthly precipitations have been shown. Monthly amounts of produced pellets during the year 2013 have been presented at left middle chart. Production is increased in months preceding winter heating season. Right middle chart illustrate average moisture contents of raw material which is affected both by time of three cutting and by precipitation intensity. Unexpectedly lower moisture content during the January and February was consequence of strong wind which dried the logs. At lower left charts monthly amounts of evaporated water in drying process have been presented. Finally, average monthly thermal power required for drying and space heating has been presented in lower right chart. It is evident that share of space heating demand is almost negligible compared to drying demand. During the three summer months required thermal power is even lover than 1 MW. In the last three months of the year when heat demand exceeds nominal thermal output of the cogeneration plants operation of peak boilers is required.

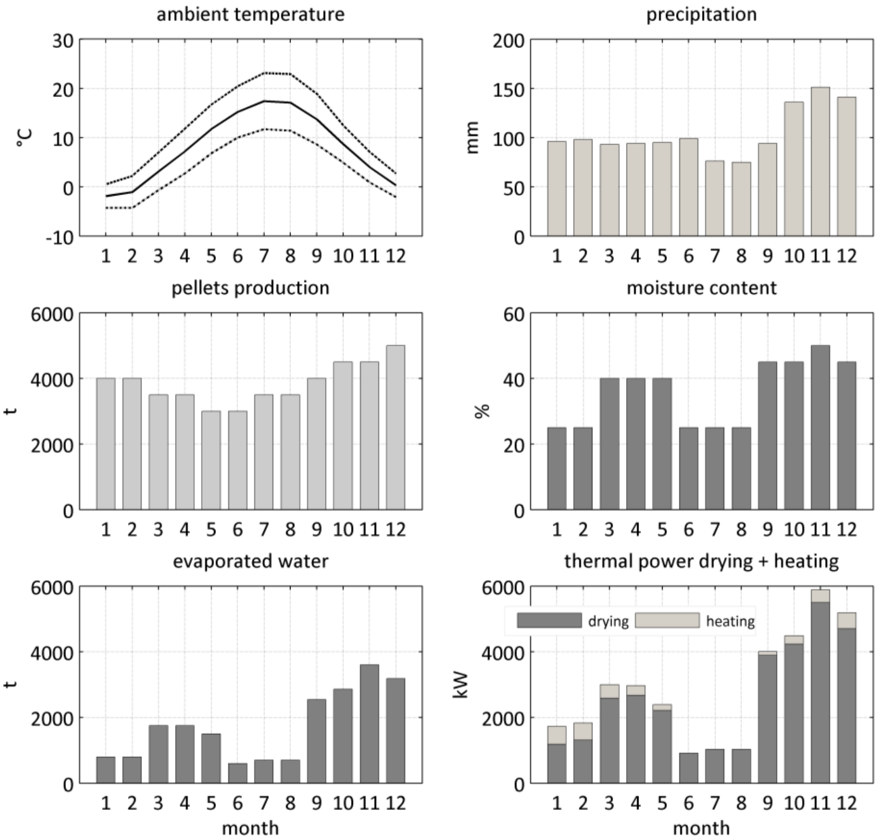

Figure 2: Heat demand estimation, average monthly temperatures, precipitation, raw wood moisture content, monthly pellets production, evaporated water and average thermal power for drying

Calculation of heat drying demand is based specific consumption of 1,100 kWh per ton of evaporated water (Thek and Obernberger, 2010). Monthly amount of evaporated water m_{eva} is determined based on initial moisture content of wet wood x_1, and monthly pellets production m_p according to Eq(1):

$$m_{eva} = 0{,}9 \cdot \left(\frac{x_1}{1-x_1} - \frac{0{,}1}{0{,}9}\right) \cdot m_p \qquad (1)$$

The calculation of space heating requirements has been performed based on monthly averages of outside temperatures and assumed specific heat demand of buildings (1.1 W/m^{3}K). For volume of 25,000 m^3 of heated space approximately 2,300 MWh is required for maintain temperature of 18 °C during the heating season (September – May).

3. Low temperature ORC plant

Since income of sold electricity is essential for plant investment payback, non-cogeneration operation mode is applied and evacuation of surplus heat through air cooled heat exchangers is usual practice. In order to replace inefficient heat utilisation additional low temperature ORC configuration has been considered. The principal scheme of future plant is presented in Figure 3, where dotted line denotes additional flows introduced by new configuration.

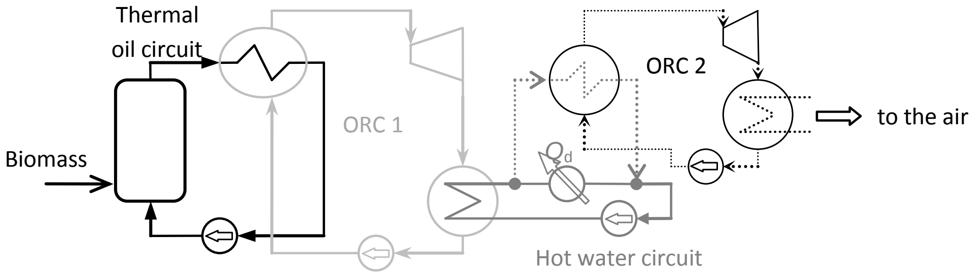

Figure 3: Simplified configuration of two ORC plant cascade

As could be seen from the results of the analysis of the heat demand, during the first eight months, required thermal power for drying, denoted as variable Q_d in Figure 3, is less than nominal thermal power of ORC 1. By adding a second system ORC 2, evacuation of surplus heat to the air currently performed at the level 80/60 °C, could be substituted by evacuation at the lower temperatures levels and by generation of additional amount of electricity.

Due to wide range of possible operating regimes determined by amounts of surplus heat and by variable ambient temperatures a simplified simulation model has been devised in order to illustrate electricity generation potential and to suggest optimal size of the ORC 2 configuration.

Following detailed comparison of various ORC configurations by unified performance indexes (Branchini et al., 2013) a similar calculation tool has been developed in order to determine influence of variable air temperature on the cycle efficiency. Developed tool is based on thermodynamic CoolProp® software for calculations of working fluids properties incorporated in MatLab® environment. Results of calculation of influence of condensing temperature on cycle net efficiency of widely spread low temperature working fluid R245fa have been illustrated in *T-s* diagrams in Figure 4.

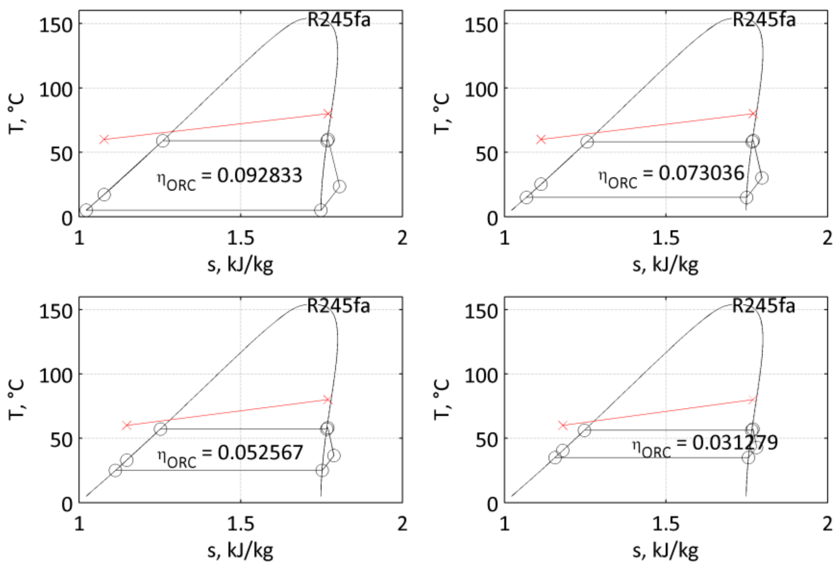

Figure 4: ORC 2 cycle net efficiencies in relation to condensation temperature, working fluid R245fa

Calculations were performed based on following assumptions: 6 °C pinch point, 1 °C superheating, 70 % of turbine efficiency, 60 % pump efficiency, 95 % recuperator efficiency and electricity consumption of air cooler fans is equivalent to 1.2 % of condensing heat. Calculated efficiencies are similar to those published in (Dalta and Brasz 2012) where research focus was on selection of appropriate working fluids for configurations of similar size. Beside influence of condensation temperature on cycle efficiency part-load operation has been also taken into account. Based on observation of part load map obtained by simulation of yearly operation presented in (Lecompte et al., 2013) simplified relation has been introduced: cycle net efficiency decrease linearly down to 50 % load and stay at 50 % for lower loads.

4. Optimal plant size

In order to compare net electricity generation of different plant sizes two nominal heat scenarios have been compared: a reference one denoted by Q_1 and inverse one, denoted by Q_2, when hypothetically is assumed that more heat is available at the beginning of the year when ambient and consequently condensation temperatures are lower. Relevant boundary conditions have been collected in Table 1.

Table 1: Boundary conditions for simulation

Month		January	February	March	April	May	June	July	August
Q_1	MW	2.3	2.2	1.0	1.0	1.7	3.0	3.0	3.0
Q_2	MW	3.0	3.0	3.0	1.7	1.0	1.0	2.2	2.3
T_{cond}	°C	7	8	14	17	22	25	28	28

In addition to nominal scenarios variations of total available heat are introduced by multiplying base scenarios with appropriate coefficient in the range between 0.8 and 1.2. Besides varying available thermal power profile in calculations nominal thermal size of plant has been varied too in the range between 1,800 kW and 3,600 kW. Results have been presented in Figure 5. Major observation could be summarised.

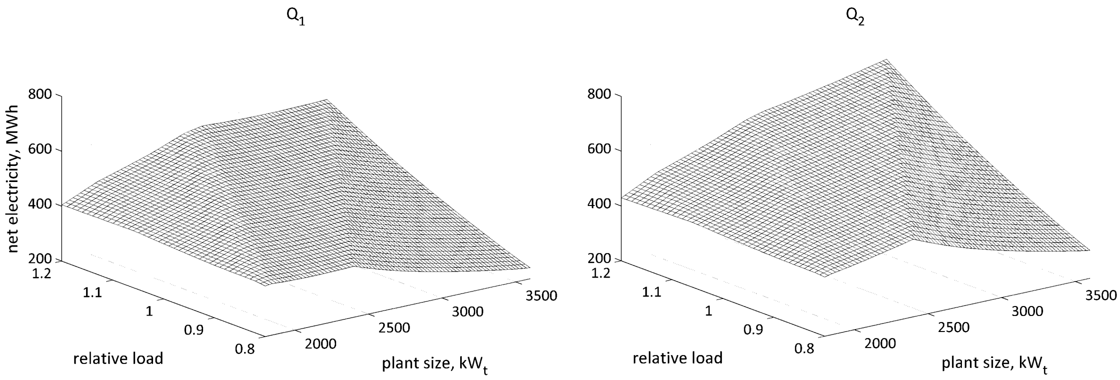

Figure 5: Net electricity generation for two heat scenarios Q_1 (left) and Q_2 (right)

Maximum net generated electricity is proportional to available heat load, higher the load higher the generation. It should be stressed that as much as accurate estimate of available heat load profile is crucial for profitable operation. Overestimated plant size could result in to long periods of non profitable part load operation.

At graph illustrating reference scenario Q_1 two local maximum could be observed. It seems that there is no significant difference between bigger plant, operating at partial load during low temperature and high efficiency period, and smaller plant operating at nominal load in winter months and not utilising surplus heat during the summer.

At graph illustrating inverse scenario Q_2 positive influence of higher load operation in winter months significantly exceeds inefficient and part load operation during the summer. Total amount of generated electricity is in general more than 10 % higher than respective amount in reference scenario.

Apart from more efficient utilisation of waste heat available and contributing to fulfilling sustainability criteria, installation and operation of low temperature organic Rankine cycle plant offer possibility of reducing local site electricity consumption or earning additional income. At current feed-in tariffs of approximately 200 €/MWh valid for biomass fired cogeneration plants in operation in Croatia with minimum yearly efficiency of heat and power generation of 50 %, exported amount of 500 MWh of generated electricity could be as high as 100,000 €/y. Looking at specific investment costs for configurations of approximate size of 250 kWe in the range between 2,700 and 3,500 €/kW_e (Lecompte, et al., 2013) rough estimate of yearly income is attractive enough to initiate more detailed analyses.

5. Conclusions

Major steps required for preliminary evaluation of viability of low temperature organic Rankine cycle configuration incorporated into existing cogeneration plant have been presented in this article. Taking operational pattern of existing plant as fixed boundary an analysis has been performed in order to find yearly profile of low temperature waste heat.

Simplified calculation procedure has been devised in order incorporate main variables influencing plant net efficiency in off design and part-load operating regimes. Results of sensitivity analyses have shown approximately linear dependency of maximum generated net electricity and cumulative heat load. In reference heat load scenario two local maximum have been be observed.

Since considered plant could gain privileged producer status and guaranteed feed-in tariff potential yearly income of exported electricity, is motivating enough for more detailed analyses of both heat profile and of market availability of low temperature systems.

Proposed approach could be utilised as a first guess in process of determining optimal size of low temperature ORC plant. It is not as detailed as hourly analysis but it is sensitive enough to illustrate influence of ambient temperature and fluctuating waste heat profile on estimate of net electricity generation.

Aknowledgement

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