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Energy Procedia 101 (2016) 822 – 829

Energy Procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Fluid Selection and Plant Configuration of an ORC-biomass fed System Generating Heat and/or Power

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Abstract

The aim of the paper is to compare from an energetic, exergetic and economic viewpoint different plant configurations of Organic Rankine Cycles matched with biomass-fired boilers for electricity production or combined heat and power generation. To this purpose, a computer tool able to perform the fluid selection and plant layout optimization has been developed. The devices efficiency charts are used to predict the components performance while the fluid thermodynamic properties have been retrieved from two databases. Results show that Toluene guarantees the highest performance in both cases while the most suitable configuration is the recuperative one.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Biomass, Cogeneration, Organic Rankine Cycles Design, Energetic, Exergetic and Economic Analysis.

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1. Introduction

The increasing global energy demand speeds up the depletion of fossil fuels, while environmental issues urgently demand to look for new and non-polluting sources. Renewable energy sources are the most promising and safety way to mitigate pollution, improve energy security and reduce fossil fuels consumption.

In this scenario, biomass is an important substitute for fossil fuels with the advantage of sustainability, environmental friendliness and good adaptability [1].

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Peer-review under responsibility of the Scientific Committee of ATI 2016.
doi:10.1016/j.egypro.2016.11.104

Nomenclature

BB	Biomass Boiler
C	cost, $
CHP	Combined Heat and Power
DHN	District Heating Network
E	recuperator efficiency, -
IP	Profitability Index, -
LCOE	Levelized Cost of Energy, $/kWh
m	mass flow rate, kg/s
n	rotational speed, rpm
NPV	Net Present Value, M$
ORC	Organic Rankine Cycle
P	Power, kW
p	pressure, bar
SP	Size Parameter, -
SPB	Simple Pay Back, year
T	temperature, °C
TIT	Turbine Inlet Temperature, °C
VFR	Volumetric Flow Rate, m^3/s
WF	Working Fluid
η	efficiency, %
cond	condensation
el	electric
ev	evaporation
ex	exergetic
th	thermal
TUR	turbine

Biomass is the result of natural organic processes; it is the fourth largest energy source in the world and contributes to nearly 14% of the world's raw energy demand [2].

Several studies have been carried out to estimate biomass potential, how the government policies can support its sustainable development and where it can be used for electricity generation (i.e. [3,4]). In particular, these researches have pointed out that biomass is well suited for decentralized, medium- and small-scale CHP systems for two reasons. On the one hand, biomass based systems can reduce fuel transportation costs if used on site. On the other hand, it is difficult to find a large end-user requiring the amount of heat produced in a large-scale CHP plant.

Considering the biomass based power generation units, the internal combustion engines coupled with gasifiers and the biomass fired thermal oil boilers coupled with Organic Rankine Cycle (ORC) modules are the most widespread technologies. However, in literature, there are different opinions about the maturity of gasification technology while Biomass Boilers (BB) coupled with ORCs are a well proved technology, not requiring high investment, operational and maintenance costs. For example, Quoilin et al. [5] estimate that a plant based on the ORC technology has an investment and maintenance cost, respectively, 75% and 200% lower than a gasification system while Schuster et al. [6] assert that ORC plants are the only proven technology for decentralized applications producing power up to 1 MW_{el} from solid fuels like biomass. In addition, BB-ORC units become even more affordable if they are linked with District Heating Networks (DHN). In Italy there are 192 DHNs located in 150 cities and 88 of them are fed by renewable energy sources. In Torino there is the largest network (467 km) while the first one was built in Modena in 1971. 84% of the networks are concentrated in Lombardia, Piemonte, Toscana and Trentino Alto Adige; only in Southern Tyrol (a Trentino Alto Adige region, Italy) there are more than seventy district heating plants based on biomass and most of them supply heat to residential DHNs [4].

ORCs have been investigated since the 1880s but they have never been popular until today's growing interest on medium and low grade energy recovery systems where cycles using water as working fluid fail for technical and economic reasons [7].

The ORC operates like the conventional steam Rankine cycle but it uses an organic medium instead of water. The ORC layout and components are also similar to the steam Rankine cycle ones.

The heat transfer from the hot side to the power cycle can be carried out in two ways: the heat source medium and the working fluid streams can directly exchange heat or an intermediate thermal oil loop is integrated to avoid risky contact between the hot fluid and the organic medium [8]. In this manner, also flammable working fluids can be employed. Note that the insertion of an oil loop is a standard for BB-ORC units.

The ORC electrical efficiency ranges between 6 and 17% [9] but, even if the efficiency is low, these plants require low maintenance work and, thus, really low personnel and O&M costs [6]. In addition, the use of an organic medium instead of water guarantees an expansion process that ends in the region of superheated vapor; a fact that avoids turbine's drops erosion and allows a reliable operation and a fast startup of the cycle.

Notwithstanding the above mentioned aspect, the ORC configuration and the setting of the operating parameters are affected by the choice of the organic WF [5,8]. For this reason, several studies have been conducted in order to find out the optimal fluid (see i.e. [5,8,10]). The fluid selection is a complicated task because hundreds of substances can be used as WF candidates and, based on the works available in literature, it can be concluded that an optimal fluid for all the ORC units does not exist. Hence, in the ORC design process a fluid screening procedure needs to be implemented.

In literature, several studies on ORCs coupled with biomass boilers are also available. As an example, Bini and Manciana [11] presented a comparison between a combined heat and power unit based on ORC turbogenerators and a Stirling engine while Obernberger et al. [12] described and evaluated the performance of the 1 MW_{el} BB-ORC plant installed in Lienz. Technical and economic aspects of biomass fueled CHP plant based on ORC turbogenerators feeding a DHN have been analyzed in [13] and [14] while in [5] the energy performance of a similar plant have been monitored. An extensive literature review concerning the development of small and micro scale biomass-fueled CHP systems has been presented in [2] while a survey of existing small-scale CHP plants in Sweden and Finland is summarized in [15].

From the above survey, it can be checked that several researchers worked about fluid screening or technical and economic aspects related to the BB-ORC coupled with DHN, but there is a lack of a thorough comparison between the fluids which can be employed in a BB-ORC working in cogeneration mode or producing only electrical energy. This topic attracted the interest of an Italian biomass boiler manufacturer which wants to develop a BB-ORC plant able to operate both in cogeneration and in electric production mode. For this reason, the Authors have developed a computer tool able to perform the fluid selection and the plant layout optimization of the ORC unit producing heat and power or only electrical energy. The comparison between the two operation modes has been performed based on an energetic, exergetic and economic point of view.

The rest of the work is organized as follows: the selected case study and the developed model are presented in Section 2 while the optimization results are outlined and discussed in Section 3. Conclusions remarks are given in Section 4.

2. Theory and Methodology

Biomass-fired CHP plants based on the ORC technology with size in the range 400-1500 kW_{el} have been successfully demonstrated and are commercially available from several manufacturers while the implementation of ORC in small and micro-scale biomass-fired CHP systems is encountering several technical (primarily the limited electric efficiency) and economic (high specific investment costs) obstacles [2]: for these reasons, several industries are engaged in the development of different scale ORC power systems. The aim of the present work is to develop an ORC plant coupled with a biomass boiler able to operate both in cogeneration and in electricity production mode without introducing layout or fluid modifications.

At the time of writing, the manufacturer produces Biomass Fired Hot Gas Generators, Biomass Fired Steam Boilers and Biomass Fired Thermal Oil Heaters with size in the range 300 kW_{th} - 18 MW_{th}. In order to develop a power system able to compete with the commercialized ones, the manufacturer suggests to use a boiler with a design thermal power of 3 MW. An intermediate thermal oil loop is needed in order to avoid risky contact between the hot exhaust gases and the ORC working fluid. Therefore, the boiler is a moving grate furnace Biomass Fired Thermal Oil Heater fed with woodchips (G30-G50). Table 1 lists the boiler design characteristics. Note that the feedstock is pre-treated in a drying section till the water content is in the range 15 e 20% on a wet basis. After that the biomass is loaded into the boiler by means of racks moved by hydraulic cylinders.

Table 1. Biomass Fired Thermal Oil Heater design specifications.

Parameter	Value
Design power	3 MW
Oil mass flow rate	24 kg/s
Maximum oil delivering temperature	310°C
Minimum oil return temperature	250°C

Being the ORC performance influenced by the boiler operation, the model of the biomass drying section and of the thermal oil heater have been firstly built. Then, the BB model has been linked with the ORC plant designer [16]. A sketch of the power system is depicted in Fig. 1. Specifications regarding the boiler model and the biomass characteristics cannot be published.

The tools have been fully implemented in MATLAB environment [17]. The ORC plant designer model uses the genetic algorithm toolbox to perform the optimization. It is a versatile computer tool able to select the appropriate working fluid and plant architecture starting from different types of heat source. The most appropriate WF is selected among 115 pure working fluid candidates. The available fluids are HydroCarbons, HydroFluoroCarbons, Siloxanes, PerFluoroCarbons, HydroChloroFluoroCarbons, ChloroFluoroCarbons, HydroFluoroOlefins, Ethers, Inorganics, Alcohols and Esters. These fluids are not available in a unique database, therefore the tool is linked with REFPROP [18] and CoolProp [19] databases. The use of two databases guarantees a larger number of fluids and compensates the fluids' lack that can occur using a single library.

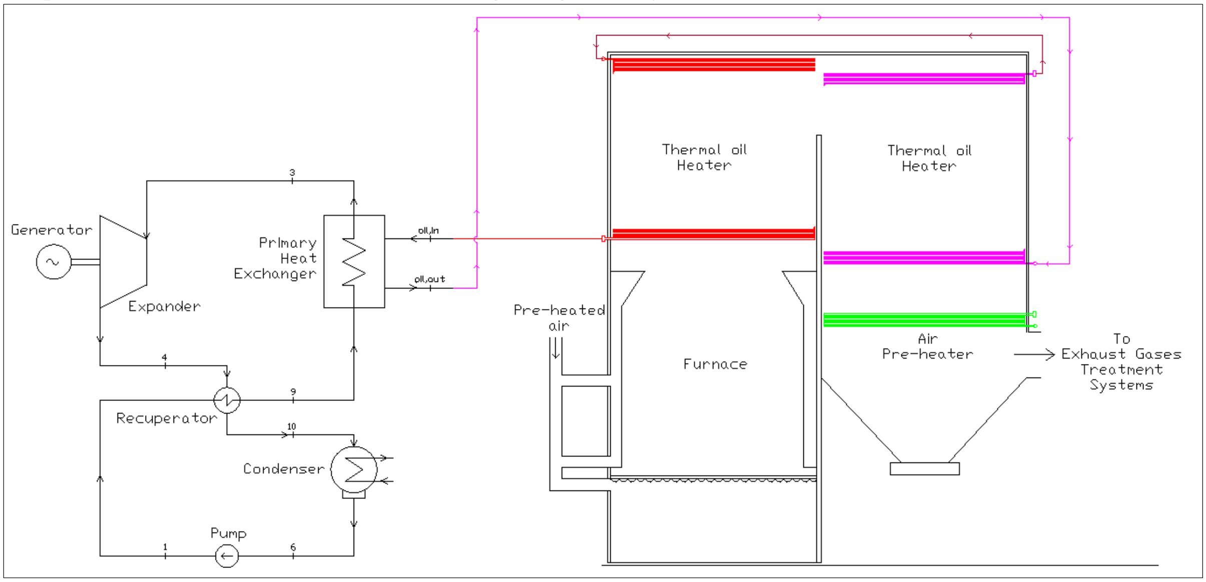

Fig. 1. Scheme of the biomass boiler and the organic Rankine cycle unit.

During the optimization process the objective functions that can be selected and optimized are the net electric power (P_{el}), the thermal (η_{th}) and exergetic efficiency (η_{ex}), the Profitability Index (IP), the Net Present Value (NPV), the Simple PayBack Time (SPB) and the Levelized Cost of Energy (LCOE). The user can also select between a single or a multi-objective optimization approach.

The equations used to compute these functions are summarized in [16,20]. The input parameters are the heat source medium (thermal oil), the inlet temperature, pressure and mass flow rate of the thermal oil (which are computed with the Boiler model), the pump mechanical and isentropic efficiency, the electric motor efficiency, the expander mechanical efficiency and the electric generator efficiency. Table 2 reports the efficiency values assumed for each component in the present simulation.

Table 2. Efficiency values assumed for the ORC optimization.

Parameter	Value
Pump isentropic efficiency	0.75
Electric generator efficiency	0.94
Pump electric motor efficiency	0.90
Pump mechanical efficiency	0.95
Turbine mechanical efficiency	0.92

For each WF, the variables that are optimized by the tool are the thermal oil outlet temperature, the evaporation pressure of the organic medium, the turbine inlet temperature and the recuperator efficiency. The minimum temperature difference in the condenser, recuperator and primary heat exchanger are also optimization variables. Note that the not predefined pinch point position and the not fixed pinch value are innovative characteristics implemented in the tool. The optimization variables need to be limited in order to design a feasible plant. The upper and lower bounds established for each of them are listed in Table 3.

Table 3. Upper and lower bounds fixed into the ORC plant designer tool.

Parameter	Lower Bound	Upper Bound
Heat source outlet temperature	250°C	300°C
Evaporation pressure of the organic medium	Condensation pressure	Critical pressure
Recuperator efficiency	0	0.8
Minimum temperature difference in the heat exchangers	10°C	40°C

The Turbine Inlet Temperature upper and lower bounds are assumed with the procedure described in [16] while the value assumed for the condensation temperature is 40°C when the plant produces electrical power and 95°C when the plant is a CHP unit. Note that the condenser is fed by cold water coming from an air cooler when the plant is not cogenerative. In this condition, the air flow is assumed to enter at 30°C, a typical summer air temperature in Italy. The air cooler investment and operating costs are considered in the economic analysis. This is a novelty because the circulating pump and fans electric consumption are usually neglected.

The remaining variables (working fluid mass flow rate, thermodynamic state point, electric power produced by the plant, mass flow rate of the medium used into the condenser, etc.) are computed during the optimization procedure because they are “dependent variables”.

The recuperator efficiency is defined as outlined in [21] while the isentropic efficiency of the expander is estimated by the axial and radial flow turbines efficiency charts [22,23]. In this way for each fluid, during the optimization process, the optimizer computes the size parameter and the volumetric flow rate, as defined in [22,23], then interpolates the efficiency charts and calculates the turbine isentropic efficiency for both the axial and radial configuration, respectively. The higher isentropic efficiency is selected by the tool to perform the optimization.

The heat exchangers, the feed pump, the expander, the air coolers and the thermal user pump performance and costs are also taken into account during the optimization process.

Several checks are also implemented into the code to avoid pinch point violation in the heat exchangers, the presence of liquid at the turbine inlet and low value of steam quality at the turbine outlet. A further check controls that the evaporation process starts into the recuperator.

The equations adopted in the energetic, exergetic and economic analysis are retrieved from [16,20]. Note that the expected plant life, the plant availability factor, the electricity sell price, the interest rate and the corporate tax rate are assumed equal to 15 years, 0.85, 0.31 $/kWh$_{el}$, 6%, 45%. The biomass specific cost and the heat sell price are assumed equal to 80 $/kWh and 0.29 $/kWh$_{th}$ respectively.

Finally, the tool has been validated with the plant specifications reported in [4]. The discrepancy between the tool results and the ones outlined in the Reference are lower that 1% and mainly related to the adopted optimization algorithm and working fluids database.

3. Results and Discussion

The maximization of the net electric power, the Profitability Index and exergetic efficiency are the three objective functions employed to optimize the BB-ORC cogenerative and not power unit.

As depicted in Figure 2, the highest net electric power, Profitability Index and exergetic efficiency are reached with Toluene as working medium if the non-cogenerative scheme is considered. This fluid supplies higher net electric power than using E-benzene (0.9%), O-xylene (1.2%) and M-xylene (1.5%). An increase of the thermal and exergetic efficiency higher that 1% are also observed. An ORC using O-xylene instead of Toluene, brings lower evaporating and condensation pressure but higher equipment costs. Also the SPB of the ORC that employs O-xylene is lower than the one using Toluene. The recuperator efficiency reaches 80% in the case of Toluene, O-xylene and M-xylene while it is 6.3% lower if E-benzene is employed. However, whatever fluid is adopted, the expander is an axial machine. The turbine isentropic efficiency is equal to 76.4% if Toluene is adopted while it is 73.4% in the case of O-xylene.

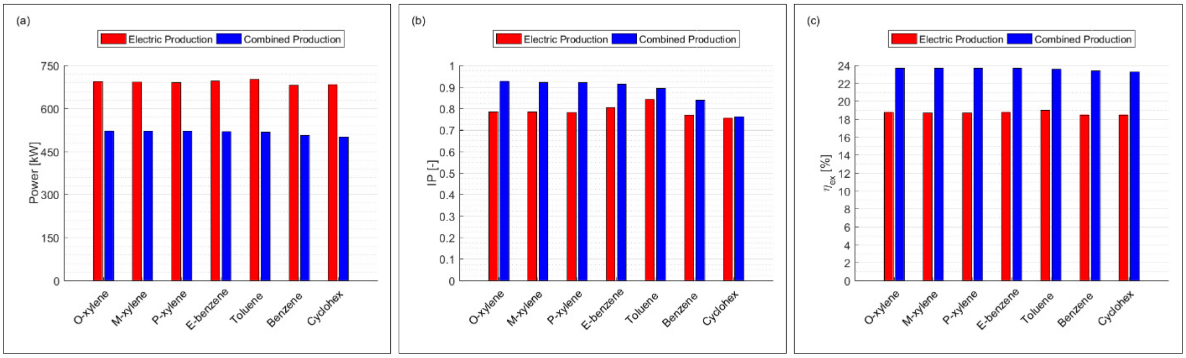

Fig. 2. Optimization results for the two configurations.

The use of O-xylene guarantees the maximization of the net electric power and of the IP if the ORC unit is cogenerative while the maximum exergetic efficiency can be reached adopting O-xylene, P-xylene, M-xylene or E-benzene. Note that O-xylene guarantees the maximum net electric power but the difference between O-xylene and P-xylene and M-xylene is really small (1 kWel). As depicted in Fig. 2, the use of O-xylene increases the net electric power by 1 kW_{el} compared to the case of P-xylene/M-xylene and of 3 kW_{el} and 4 kW_{el} compared to E-benzene and Toluene respectively. As for the non-cogenerative configuration, O-xylene, P-xylene and M-xylene bring lower evaporating and condensation pressure than using E-benzene and Toluene as working medium. The expander machine is an axial turbine while the recuperator efficiency reaches 80% for all the WFs depicted in Fig. 2. The ORC equipment costs are more or less the same if E-benzene, O-xylene, P-xylene or M-xylene are employed while an increase of 1.5% is observed if Toluene is used as WF.

Table 4, 5 and 6 list the optimization variables, the expander characteristics, the thermal and exergetic efficiency and the economic indexes of the most promising fluids for each configuration. The listed results refer to the maximization of the net electric power, in agreement with the aim of the manufacturer.

In order to fulfill the objective of the present work, the Authors compare cogenerative and no-CHP configurations. It is immediately clear that Toluene guarantees the best performance in the case of non-cogenerative plant while O-xylene brings the higher energetic, exergetic and economic parameters for the CHP plant. Therefore, apparently, there is not a fluid able to assure the highest performance in both cases.

The results listed in Table 4, 5 and 6 show that O-xylene produces an electric power that is only 1.5% lower than in the case of Toluene (non-cogenerative scheme) while using Toluene in a CHP configuration reduces the net electric power less than 1%. But, a higher increment of the purchasing costs and SPB are observed, 1.5% and 1.8% respectively. In addition, using O-xylene instead of Toluene, brings lower condensation pressure, a fact that increases the condenser purchasing costs and the plant complexity.

Starting from the performed analysis, the Authors suggest to adopt Toluene as working fluid. However, they also suggest to study the behavior of the optimized configuration during part-load and dynamic operation modes in order to understand what optimized ORC unit guarantees the highest performance in CHP and in non-cogenerative mode. After that, experimental measurements are also paramount to describe the real behavior of the plant working both in electric and in CHP mode.

Table 4. ORC's main parameters.

Configuration	Fluid	P_{el} [kW]	m_{ORC} [kg/s]	TIT [°C]	p_{ev} [bar]	p_{cond} [bar]	m_{water} [kg/s]
Electric Production	Toluene	702	4.83	279.85	18.95	0.08	50.68
	E-benzene	696	4.81	278.85	11.52	0.03	50.86
	O-xylene	694	4.78	279.85	9.64	0.02	50.30
CHP	O-xylene	522	5.63	278.85	8.76	0.22	27.73
	P-xylene	521	5.79	279.85	9.87	0.27	27.34
	M-xylene	521	5.74	279.85	9.81	0.26	27.35
	E-benzene	519	5.82	277.85	10.37	0.29	27.76
	Toluene	518	5.74	279.85	17.35	0.64	27.76

Table 5. Recuperator efficiency, expander parameters and thermal and exergetic efficiency.

Configuration	Fluid	η_{ex} [%]	$\eta_{th,ORC}$ [%]	$\eta_{is,TUR}$ [%]	n_{TUR} [rpm]	SP [m]	VFR [-]	E [-]
Electric Production	Toluene	19.0	24.0	76.4	7339	0.218	236.45	0.80
	E-benzene	18.8	23.9	76.3	4645	0.344	379.95	0.75
	O-xylene	18.8	23.8	73.8	5597	0.402	430.35	0.80
CHP	O-xylene	23.7	17.9	74.6	8043	0.158	39.48	0.80
	P-xylene	23.7	17.9	76.5	8579	0.146	37.31	0.80
	M-xylene	23.7	17.9	76.5	8544	0.147	37.83	0.80
	E-benzene	23.7	17.8	76.5	8798	0.141	37.72	0.80
	Toluene	23.6	17.7	76.5	12652	0.099	29.04	0.80

Table 6. Economic analysis results.

Configuration	Fluid	IP [-]	C_{ORC} [k\$]	VAN [M\$]	LCOE [\$/kWh]	SPB [year]
Electric Production	Toluene	0.84	1292	2.671	0.1632	5.27
	E-benzene	0.82	1296	2.599	0.1646	5.34
	O-xylene	0.78	1327	2.526	0.1611	5.44
CHP	O-xylene	0.93	1146	2.746	0.2129	5.04
	P-xylene	0.92	1150	2.728	0.2134	5.06
	M-xylene	0.92	1149	2.731	0.2133	5.06
	E-benzene	0.91	1147	2.711	0.2141	5.08
	Toluene	0.89	1163	2.667	0.2155	5.13

4. Conclusion

Renewable energy sources are the most promising way to mitigate environmental impact, improve energy security and reduce fuel consumption. In this scenario, biomass is an important substitute for fossil fuels and it is likely to be a good option for electricity generation or cogeneration purposes in the next future.

Biomass boiler coupled with Organic Rankine Cycle is an effective way to produce electricity or heat and power from biomass. To this purpose, an Italian boiler manufacturer is interested to develop an ORC unit able to produce electricity or heat and power.

In the present work, a mathematical model of the boiler and of the ORC unit have been developed in order to find out the best ORC working fluid and plant configuration that guarantee to operate the plant both in CHP mode and in only electricity production mode. The optimized configurations have been analyzed from an energetic, exergetic and economic viewpoint.

Results show that Toluene can be a good working fluid for both operation modes while the most suitable configuration is the recuperative one. However, a part-load and dynamic analysis coupled with experimental measurements are paramount to predict the real plant performance, the working fluid stability and the unit costs.

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