

ORGANIC RANKINE CYCLE TURBOGENERATORS FOR COMBINED HEAT AND POWER PRODUCTION FROM BIOMASS

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1. INTRODUCTION

The Organic Rankine Cycle (ORC) is similar to the cycle of a conventional steam turbine, except for the fluid which operates in the turbine, that is a high molecular mass organic fluid.

The high molecular mass working fluid allows to exploit efficiently low temperature heat sources to produce electricity in a wide range of power outputs (from few kW to some 2.5 MW electric power per unit).

The following advantages are obtained

- High cycle efficiency.
- Very high turbine efficiency (up to 85 percent).
- Low mechanical stress of the turbine, due to the low peripheral speed.
- Low RPM of the turbine allowing the direct drive of the electric generator without reduction gear
- No erosion of blades, due to the absence of moisture in the vapour nozzles.
- Long life.

There are also many other advantages, such as simple start-stop procedures, quiet operation, minimum maintenance requirements, good part load performance.

2 - THE CONCEPT

With reference to Fig.1, the organic working fluid (confined in a closed and leakage-free circuit) is pre-heated and vaporised using the heat of the hot source in the evaporator (shell-and-tube heat exchanger).

The organic fluid vapour expands in the turbine and is then condensed using cold water in the shell-and-tube heat exchanger (alternatively, ambient air can be used for cooling).

The condensate is pumped back to the evaporator thus closing the thermodynamic cycle.

Hot and cold sources are not directly in contact neither with the working fluid nor with the turbine.

For high temperature applications, a regenerator downstream of the turbine is also added, to further improve the cycle performance.

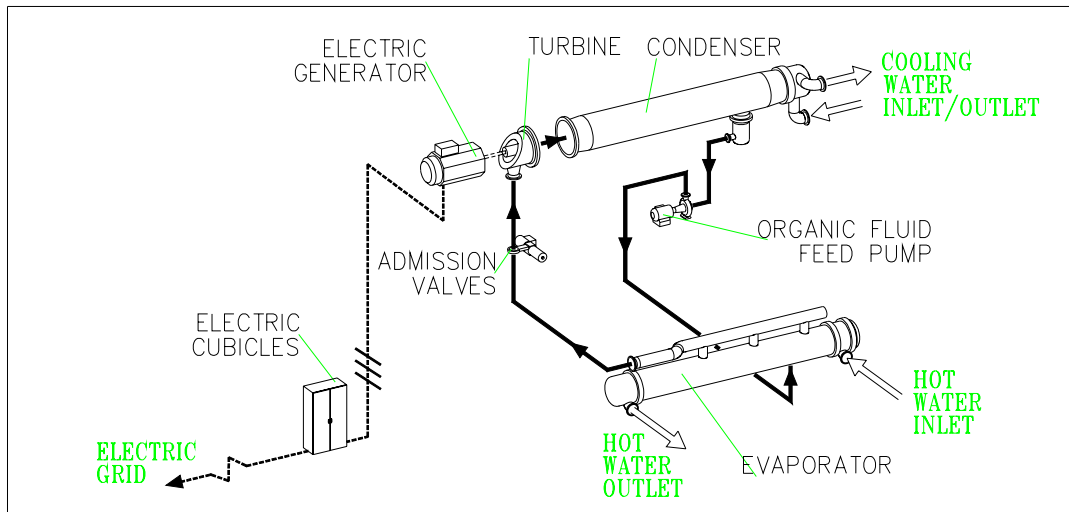


Fig. 1 - Typical Cycle Scheme [1]

3 - MODULARITY

For a power output up to 400÷500 kWel a single skid can contain all the required equipment (i.e. heat exchangers, piping, working fluid feed pump, turbine, electric generator, control and switch-gear).

Hence the machine is easy to transport, to move and to install and assembled and tested at factory.

For a higher power output a number of identical skid can be used, to be connected in parallel.

Fig. 2 - Organic Rankine Cycle Turbogenerator ready to be transported to its final installation place [2]

4 - BIOMASS APPLICATIONS

Biomass has always been used for house ambient heating. Its use for electric / thermal energy production in higher power plants has spread in recent times, due to the presence of the following positive aspects:

- biomass is an environment friendly energy source (the CO₂ produced with wood combustion had previously been accumulated from the environment during biomass life, so that the net CO₂ production in the whole process is practically zero).
- a large biomass quantity is available, due to:
 - residual products from pruning.
 - residual products from virgin wood working
 - periodical forest maintenance
 - plant cultivation directly aimed at biomass production (thanks to the policy of set-aside, a lot of area in Europe will be available in future, which could not be used for alimentary growing).

Many biomass fired plants for district heating already exist, having a power from a few kW to several MW, in particular in some countries like Denmark and Austria. These plants show the technical and economical feasibility of such applications in an industrial scale.

In northern Europe straw is being used for heat and electric energy production for more than a decade [3].

4.1 - Possible solutions for electric energy production from biomass

The exploitation of biomass for the production of electric energy can be done mainly in the following ways:

- a) biomass gassification and use of the gas as fuel for internal combustion engines (Otto cycle), gas turbines or Stirling engines.
- b) biomass fired boilers aimed at the following targets:
 - b1) production of steam to feed a traditional steam turbine
 - b2) production of hot thermal oil to be used as hot source in ORC turbogenerators.

Gassification plants (a) with gas turbines will be economically feasible only in medium - large scale (installed electric power above 1 - 5 MW), due to the complexity of the gassification process and because the gas turbine exhibits low efficiency below 1 MW electric.

As regards water steam technology (b1) the thermodynamic efficiency of such plants is good only for relatively high powers (approximately $> 2 \text{ MW}_{el}$). Moreover, the use of a boiler that produces pressurised steam requires the presence of licensed operators in a number of countries.

The turbine should be supplied with super-heated steam, in order to avoid the formation of liquid drops which would erode the turbine blades and decrease its fluid-

dynamic efficiency. For this reason the boiler should have a super-heater too, thus resulting in higher complexity and cost, especially for low power plants.

In fact, a lot of small steam plants (10-100 kW_{el}) have been installed in South-East Asia (Thailand, Malaysia, etc.), having very low efficiencies (about 10%, but sometimes down to 4-5%).

Organic fluid turbogenerators (**b2**) represent a valid alternative to steam turbogenerators for biomass applications with electric power values below 1 MW_{el}, for the following reasons:

- they do not require the adoption of boilers equipped with super-heaters;
- conversion efficiencies are high (typically 15-20%) even for powers of 200 kW electric and below;
- they have a high reliability and require little maintenance (the reason being that the working fluid is not corrosive and has a cleaning effect on the internal surfaces).
- they do not require the presence of specific licensed operators, as thermal oil is used as thermal medium.

4.2 - Combined electric energy and heat production through organic fluid turbogenerators

In Fig. 3 a scheme of plant is reported, in which a 400 kW_{el} organic fluid turbogenerator is adopted, for the combined production of electric energy and heat for district heating starting from biomass.

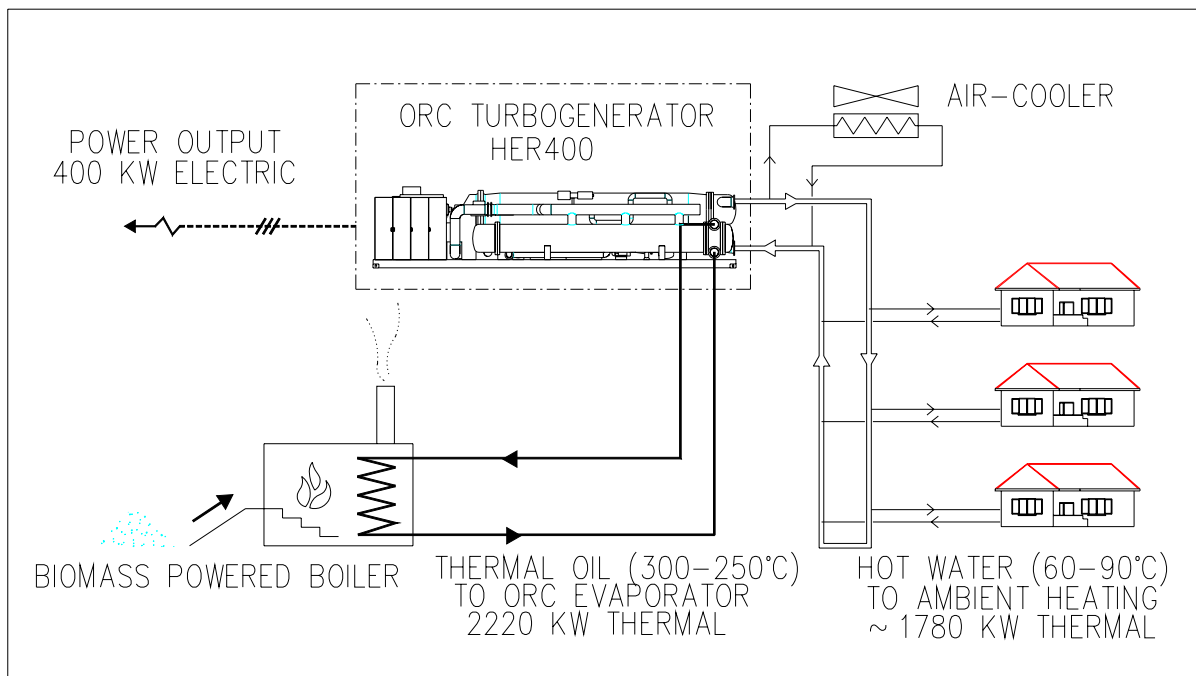


Fig. 3 - Scheme of an ORC turbogenerator for the combined production of electric energy (400 kW_{el}) and heat, starting from biomass.

DATA SHEET

Thermal source	thermal oil in closed loop
Thermal oil nominal temperature (in-out)	300 / 250 °C
Thermal oil flow rate	~ 16 kg/s
Available thermal power	2220 kW _{th}
District heating water flow rate	14.2 kg/s
District heating water temperature (in/out)	60 / 90 °C
Thermal power available to district heating	~ 1780 kW
Net electric power output	400 kW _{el}
Efficiency (electric power / thermal power)	0.18
Electric generator	asynchronous, 3-phase, 400 V, 550 kVA

Fig. 4 - Data sheet for the turbogenerator described above (Fig. 3).

The data sheet reported in Fig. 4 shows how the use of combined heat and electricity production could allow a complete exploitation of the energy source.

4.3 - Production of electric energy only

When the heat production for district heating is not required, the condenser of the turbogenerator can be cooled either by water (in a closed loop to be coupled with cooling towers) or directly through air-coolers. In this case, the adoption of a cascaded scheme can be useful, if the plant size is sufficiently large (> 500 kW_{el}).

In such a scheme, one turbogenerator uses the heat available from the hot source (by means of an exhausts/thermal oil heat exchanger) while a second turbogenerator uses the heat discharged at the condenser of the first turbogenerator. Moreover, this second turbogenerator can conveniently use the heat available from hot water 70-90 °C, coming from another heat exchanger installed after the one exhausts / thermal oil. The cascaded scheme is reported in fig. 5.

One such plant is currently under construction for the heat recovery from the gases of a foundry near Brescia, Italy. This plant will feature a net electric output of 910 kW_{el}.

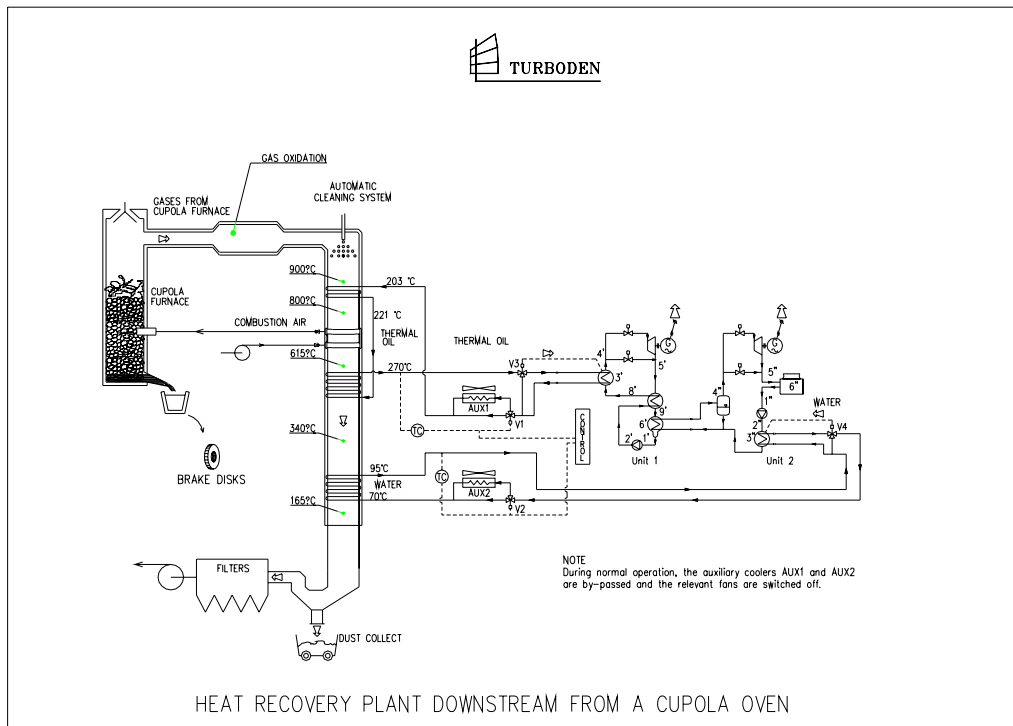


Fig. 5 - Cascaded ORC plant for heat recovery from a foundry (910 kW_{el} net).

5 - BIOGAS

Another interesting application is represented by the heat recovery from biogas fired engines.

An ORC turbogenerator coupled to a 1000 kW_{el} internal combustion engine is shown in fig. 6. The turbogenerator uses the waste heat available from the engine cooling (hot water) and that the exhaust gases. The electricity production of the gas engine can be increased up to a remarkable 12 ÷ 15 % by the adoption of the ORC.

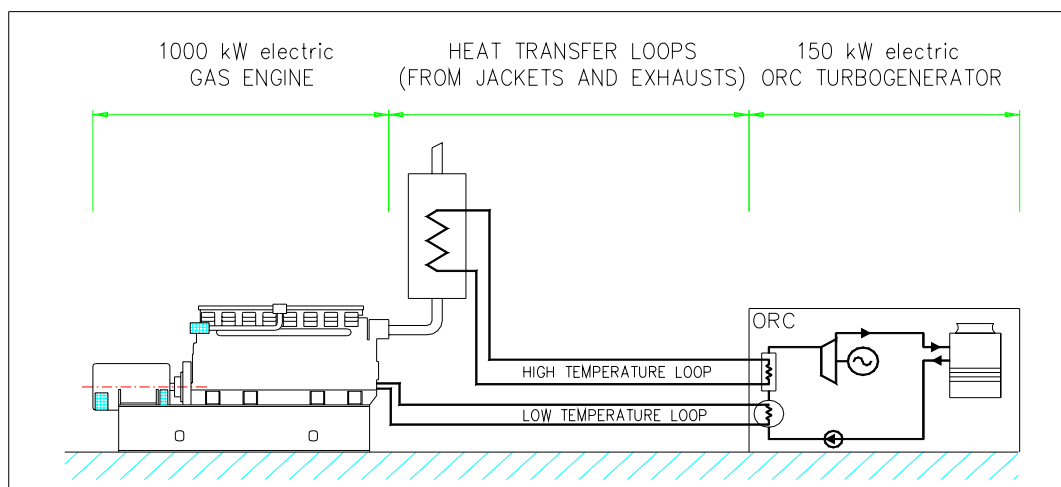


Fig. 6 - Coupling of an ORC turbogenerator to a biogas powered engine to increase the global efficiency [4].

6 - SMALL PLANTS FOR THE COMBINED PRODUCTION OF ELECTRICITY AND HEAT

Turboden is going to realize a small plant for the combined production of electric energy and heat ($10 \text{ kW}_{\text{el}}$ - $60 \text{ kW}_{\text{th}}$). This turbogenerator is the evolution of a 3 kW_{el} pilot plant, which has been constructed and successfully tested some years ago.

The new machine is the result of a co-operation between Turboden and a German society leader in the construction of biomass fired boilers. Heizomat will supply an automatically fed wood boiler.

The boiler will supply hot thermal oil to the ORC turbogenerator, as shown in the scheme of fig. 3 reported above. About 60 thermal kWth will be available from the turbogenerator condenser (hot water for ambient heating).

7 - COMPARISON BETWEEN THE ORC AND THE STIRLING CONCEPT

The main features of the Stirling engine for small scale power generation are the following:

- the working fluid is an inert gas;
- the cycle, thanks to the regeneration, efficiently exploit the available temperature difference between the “hot” and “cold” source (realizing in the ideal case the Carnot efficiency).
- the maximum cycle temperature is not limited by the working fluid, which has no decomposition problems, hence efficiencies in the range 30 to 40 % are possible and were indeed reached in some fuel powered engines.

These advantages justify the enormous research effort which has been dedicated to the Stirling concept, in its various forms.

However, the use of Stirling in practice has been hindered by a number of problems, which become even more evident when biomass is the selected energy source.

Some of these aspects are discussed in the following list, which is not exhaustive.

- a) In order to obtain a good cycle, the volume of the high temperature heat exchanger must be low, compared with the swept volume of the cylinder [5]. As a consequence, heat exchange surface will be small. The heat exchange matrix will be subdivided in small passages with low hydraulic radiuses, in order to obtain a high surface to volume ratio and to increase the heat exchange coefficient. These characteristics do not match well with biomass combustion gases, which are loaded with particulate. This problem leads to select low temperature in the cycle, hence to accept efficiencies which are much lower than the ones to be expected from a Stirling system.
- b) The volume flow in reciprocating machines is proportional to the rotational speed and the swept volume. The rotational speed is inherently limited by the lack of lubrication in the cylinder, hence to limit the swept volume, for a given output

power,(and also for a better thermodynamic performance) the gas pressure must be kept very high (often 50 to 500 bar).

- c) Sealing of fluid and wear of sliding parts in absence of lubrication are still serious problems.

The aspects presented above make the Stirling a difficult cycle to be implemented efficiently, in order to construct commercial, low cost and reliable machines.

In the ORC the maximum cycle temperature is limited by the thermal stability threshold of the working fluid down to 250 to 350 °C, depending on the selected fluid. Hence the maximum efficiency is not so high as in Stirling and is inherently limited to about 30 % (or less for combined heat and power production). However, for the case of biomass combustion, very high temperatures are not easy to achieve, due to the oxygen excess required by proper combustion.

In the ORC no sliding parts are present and the heat exchange surfaces and volumes are limited only by cost considerations.

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