ORC BOTTOMING FOR COMBINED CYCLE SYSTEMS FED BY BIOMASS

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ABSTRACT

In the last two decades ORCs have been largely used to convert the heat from biomass combustion into electric energy. The success of the ORC technology for this application is mainly due to its low maintenance requirements, ease of operation and good partial load performance.

In the quest for higher efficiency systems, biomass gasification, followed by conversion to electric power in a small scale combined cycle, is very promising.

Indeed several gasification systems, integrated with gas cleaning and gas engines for power production, have been put into operation in the past, with different results depending on the adopted solution.

The paper suggests a different approach featuring an innovative gasification device, a gas turbine prime mover, and an Organic Rankine Cycle as bottoming system, typically for a power output of the combined system up around 5 MW. A preliminary study of the system performance is presented.

1. INTRODUCTION

Biomass is a very interesting source for power generation, thanks to a number of reasons, which we try and summarize here:

- it allows storage over extended periods of time, without substantial loss of energy. Hence it allows to cope with a varying power demand, in particular with a seasonally varying power demand.
- it can be transferred to other sites, though at a higher cost than fossil fuels.
- it is, or it can be made, substantially neutral concerning the introduction of carbon dioxide in the atmosphere.
- its cost is strongly related to its origin (residual biomass from agriculture and forestry, energy crop, waste from wood industry etc.), however in many cases the cost per unit of energy content is much lower than the equivalent in a fossil fuel.
- biomass can be transformed into power by quite small power units, down to about one MW of electric power and even less. Hence the related investment can be sustained by small enterprises and limited local resources can be exploited.
- due to the low power level, it is often possible to find, at least for a fraction of the year,

a suitable consumer for the thermal power associated with the generation of electric power.

- On the other hand, if the conversion to power is referred to a Rankine Cycle power plant (steam or ORC), a number of critical aspects have often hindered a more widespread utilisation of biomass for power:
- the cost per kW electric installed is rather high, typically in the range 4000 to 8000 €/kW except for large systems, which are less attractive, for the reasons considered above. An important fraction of the cost is often related to the need to reduce the emission of particulate and of gaseous/VOC pollutants into the atmosphere.
- the efficiency of conversion is up to now rather low in most installations, typically around 15 to 20%, taking into account the whole process, that is the ratio between electric energy produced and the energy content of biomass. Even lower figures can be met for co-generative plants. This low efficiency obviously has the adverse effect of reducing the amount of electric energy which can be produced by a given low cost biomass source, so that in practice, only relatively large sources can be exploited for power generation.
- moreover the ability of today's plants to follow a fast varying load is limited. Hence in the case of an isolated grid, either a mix of power sources is introduced into the grid, or the biomass power unit has to be kept running at high power condition, and the excess power is wasted.

2. DISCUSSION OF GASSIFICATION

Gasification has been proposed as an alternative solution to straight combustion, in order to overcome the problems listed above. In fact, notwithstanding a number of tentative tests, starting back to Rudolf Diesel experiments with pulverized coal, direct utilisation in internal combustion engines of solid biomass, even very finely divided, does not seem to be promising, due to the uneven properties, the energetic cost of pulverisation, the alkali content in ashes, and in general the difficulties of feeding a solid product.
Gas feeding of reciprocating engines on the contrary has been the subject of many analyses and it has been put in to effect in a large number of real applications. A large number of different solutions have been proposed and experimented for the gasifier itself, for the cleaning of the produced gas and the overall implementation of the power plant. Gas turbine systems have been considered too, mostly at larger power level than reciprocating engines.
Specific solutions for gasification are discussed in detail, e.g. in [1] and [2].
The large number of proposed solutions indicate that none is in fact totally satisfactory.
The scope of the present paper is to describe a solution involving an innovative concept gasifier, feeding a combined cycle, composed by a gas turbine and an ORC bottoming unit.

Traditionally the solutions are classified according to the following schemes:

- fixed bed Updraft in which the descending biomass moves counter-current to the ascending gaseous phase, so that the subsequent steps of the process, from the point of view of biomass, are ordered as Drying, Pyrolysis, Reduction, Oxidation (as reported in fig.1-a)
- fixed bed Downdraft in which the descending biomass moves co-current to the descending gaseous phase, so that the subsequent steps of the process, from the point of view of biomass, are ordered as Drying, Pyrolysis, Oxidation, Reduction (fig 1-b)
- fluidized bed of various kinds. In many cases the process cannot be divided in zones and it takes place instead on the surface and within each particle of solid biomass, hence all four transitions take place substantially at the same time in parallel.

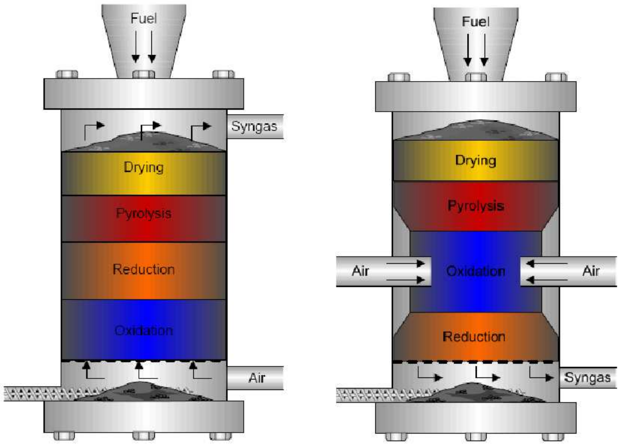

Figure 1 - Traditional fixed bed gasifier schemes [3]

In fixed bed gasifiers, Reduction is the most characterising step, which takes place in the bed of char resulting from the Pyrolysis. In Downdraft gasifiers reduction involves a given dwell time and interaction between the gases and tars resulting from the pyrolysis. As a consequence, besides the main scope of obtaining a gas composition including high H_2 and high CO, the reduction step is very effective at achieving thermal decomposition of tars. In Updraft gasifiers, the produced gas is substantially clean at the top of the reduction zone, but then it flows through the pyrolysis zone and it becomes heavily loaded with tar and moisture.
Apparently, a Downdraft solution is preferable in any case. However in practice the transfer of heat to the upper layers undergoing pyrolysis is rather ineffective and it is difficult to keep a uniform flow through the bed, in particular if the bed has a large cross section. Hence the Updraft solution, though not attractive from the tar content point of view, is preferable for relatively large systems.
Moreover so as in fact the counter-current flow of hot gas allows an efficient pre-drying of the biomass before it enters the pyrolysis zone and the separated water is added to the produced gas instead of being put to the high temperature reaction zone, allowing to feed the Updraft gasifier with high moisture biomass (up to 50% vs 20% for the Downdraft). [3]

The fluidized bed gasifiers are intermediate, for what concerns both the tar content in the gas point of view and the acceptance of high humidity feed. [4-5]
Fixed bed gasifiers are attractive due to the low parasitic power required and their tolerance of eneven quality biomass. However, the required volume of the reactor is large and the quality of the produced gas is less predictable than with fluidized bed gasifiers.

3. PRESENT PROPOSAL FOR THE GASIFIER

A different approach to the flow within fixed bed gasifiers is here proposed in conjunction with ORC bottoming solution. The new approach should allow to solve the problems reported, that is it should lead to an efficient transfer of heat to the pyrolysis zone and an efficient cleaning of gas thanks to flow within the char bed at high temperature.

The present proposal concerns an innovative co-current fixed bed gasifier, characterized by the fact of utilizing two vessels in parallel, and having an alternate flow of gasifying agent. In this way the produced gas flows back and forth through the bed, ensuring a larger volume of high temperature reactive zones, compared to a conventional downdraft gasifier. Moreover the increase of velocity through the bed activates both the heat exchange between gas and solids and the gasification reactions.
The proposed solution has been given the acronym “Twingas” by the authors of the relevant patent [6], hence here the same name is adopted, too.
A sketch of the Twingas is reported in fig. 2, concerning a system with top to bottom flow of biomass as well as an alternating co-current and counter-current flow of gas.

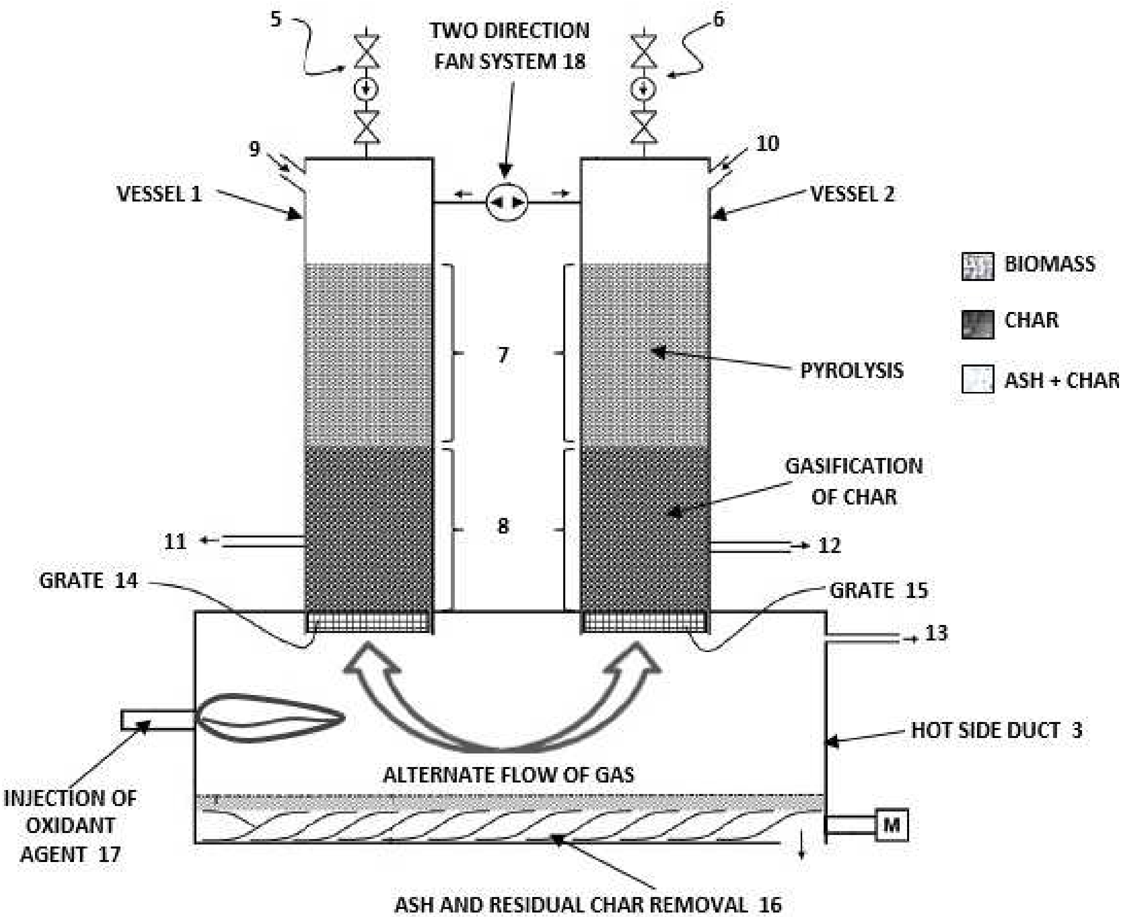

Figure 2 - TWINGAS gasifier solution, with two vessels and alternated flow of gas

The expected results are a higher production per unit of volume of gasifier, a better quality gas and a good tolerance towards non-uniform charge. Twingas is reported more in detail in Appendix I.

4. UTILIZATION OF PRODUCED GAS

The syngas produced by the gasifier can be utilized to generate power according to one of the following schemes:

1) Gas is burned in a boiler to generate organic vapour (or steam) for a Rankine cycle, preferably after some treating of the gas, e.g. to reduce the particulate content (fig. 3). Though organic vapour or steam could be also generated by burning the initial solid biomass in a suitable boiler, burning syngas gives some definite advantages, compared to a solid fuel powered furnace and boiler: the combustion can be better controlled, drastically reducing the pollutants in the exhaust, the boiler heat exchange surfaces remain clean, it is possible to change fast the flow of generated vapour/steam, in particular it is possible to reduce/shut-off quickly the combustion, in order to adapt to a the fast load change of a stand-alone unit. Moreover, the inventory of fluid in the boiler is lower, compared to a solid fuel boiler, this feature can be important if a direct exchange between combustion gas and organic working fluid is envisaged.

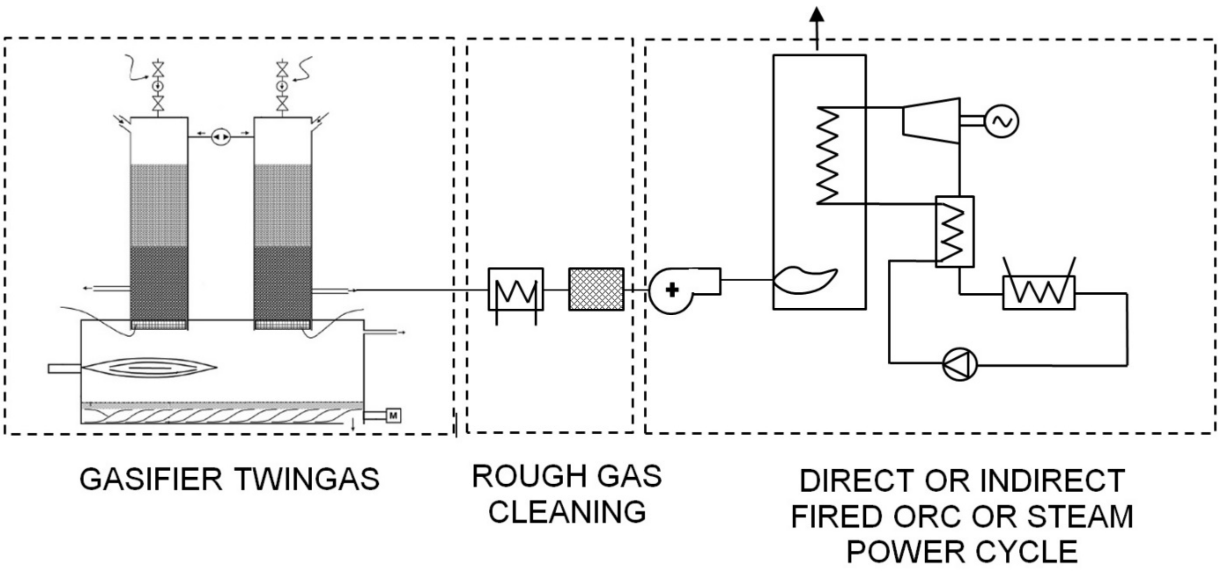

Figure 3 - Utilization of syngas for evaporation of working fluid (ORC or Steam plant)

2) Gas is thoroughly cleaned and fed to a reciprocating internal combustion engine (ICE). From the point of view of efficiency this solution is very effective, however past experience has shown that it is difficult to clean the gas consistently to a high purity level, such as to avoid a heavy maintenance burden. The thermal power available in the exhaust downstream from the engine is not large, hence a combined cycle ICE + ORC (fig.4) would get a minor increase of power and efficiency from the ORC itself (the power of the bottoming cycle amounts to some 10% of engine power).

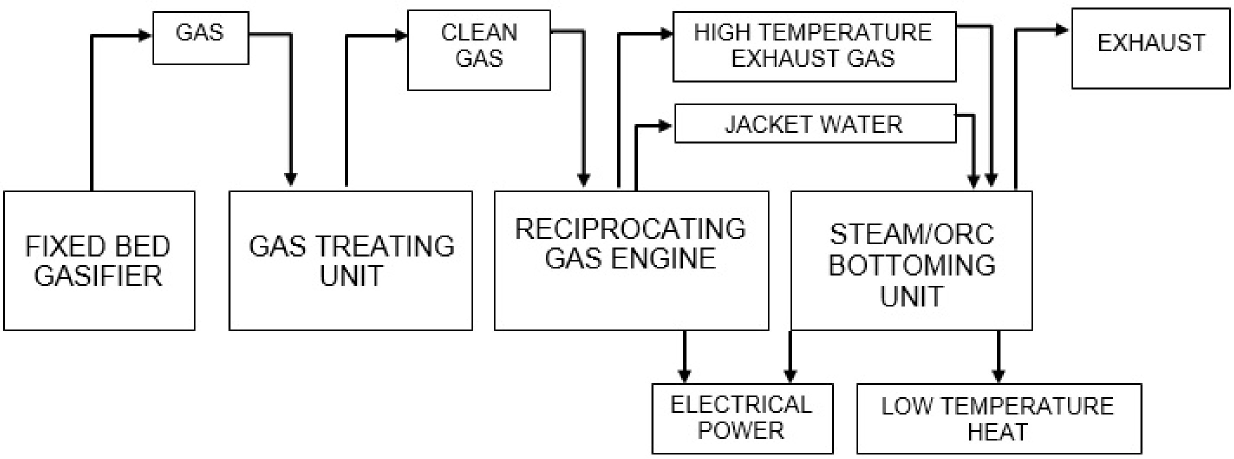

Figure 4 - Schematic of power production from fixed bed gasifier by ICE.

3) Gas is thoroughly cleaned, and fed to a compressor which in turn feeds the combustor of a gas turbine (GT). The required purity level for the gas is substantially lower for a gas turbine then for an ICE. The footprint of the gas turbine is small compared to the ICE, its exhaust gas is cleaner, the maintenance load is lower while availability and realiability are higher.
The amount of thermal power at high temperature in the exhaust is much larger than in a reciprocating engine, and the addition of a bottoming cycle is instrumental to obtain a high overall efficiency. The bottoming cycle can produce some 30% of the overall power.
The rationale for adopting an ORC solution, rather than steam are the following:
   - an ORC, if properly designed and constructed is a very reliable, long lasting, and easy to operate unit, featuring a moderate pressure and low rpm turbine,
   - the maintenance cost for ORC is low compared to steam system,

- the ORC concept allows to exploit efficiently low power sources, by adopting suitable working fluid and optimized cycle for the specific heat source,
- fast and repeated start/ stop operation and load variation can be easily fulfilled.

A schematic of the solution is reported in fig.5, with reference to an ORC bottoming unit.

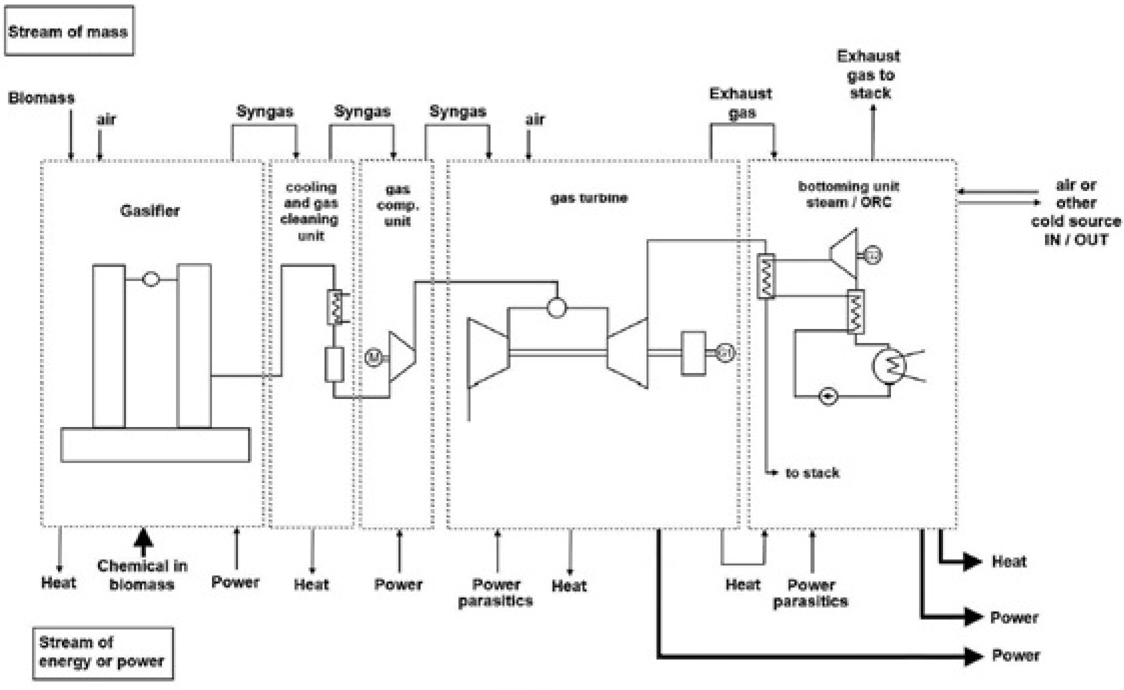

Figure 5 - Schematic of combined cycle fed by gasifier: mass and power streams

The proposed solution for the gasifier should allow to obtain a reliable, low tar, low particulate gas source.
In fact, the best option from the energy efficiency point of view involves the production in the gasifier itself of a pressurized high temperature syngas, hence the whole gas production and supply line to the gas turbine combustor must be under sufficient pressure for power modulation of the gas turbine. To avoid the deposition of its (albeit small) tar content, the temperature of the gas should be kept above some 400 °C.
A preliminary calculation has been performed for a power plant utilizing an OPRA OP16 Gas Turbine [7], organized in a combined cycle, fed by a pressurized Twingas fixed bed gasifier. The bottoming cycle for the combined cycle has been identified as a standard unit (TD 7 by Turboden, with direct recovery from gas turbine exhaust). The working fluid adopted in this case hexamethyldisiloxane.

A simplified scheme is reported in fig.6, featuring direct heat exchange between turbine exhaust gas and ORC working fluid.

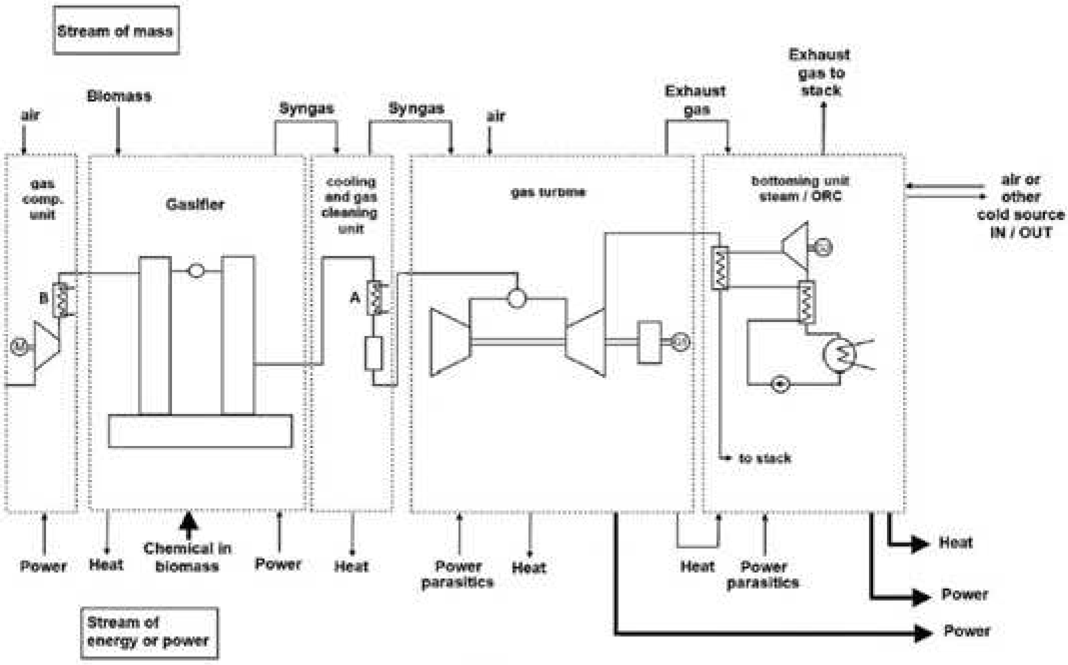

Figure 6 - Schematic of ORC combined cycle fed by pressurized Twingas gasifier: list of mass and power streams

The data adopted for a preliminary evaluation of performance for a case of power only production are reported in Table I ("Standard ORC"), while the preliminary performance is reported in Table II. The design point characteristics for the TD 7 ORC are reported in Tab III [8].

5. ENHANCED ORC BOTTOMING SOLUTIONS

The example reported in the previous chapter concerns the adoption of a standard unit of Turboden as bottoming. In order to explore the power which could be recovered by an ORC system put to the limits, an optimized recovery system has been considered, with two units in series on the exhaust. Moreover, a very high temperature supercritical cycle has been envisaged. The purpose is both to increase the temperature level of the heat input the "high side" of the exhaust flow and to lower the temperature of the exhaust gas leaving the unit, on the "low side". The same working fluid, hexamethyldisiloxane, is adopted in the two cycles, which can be linked in order to take advantage of a number of shared auxiliaries.
The exchanged power vs temperature diagram is reported in fig.7, and the expected performance is summarized in Table I to III and fig. 8 ("Enhanced ORC"). The power increase is obvious, besides the uncertainties linked to the thermal endurance of the working fluid, in any case the power increase would be obtained at the expense of increased capital cost, and complexity of system.

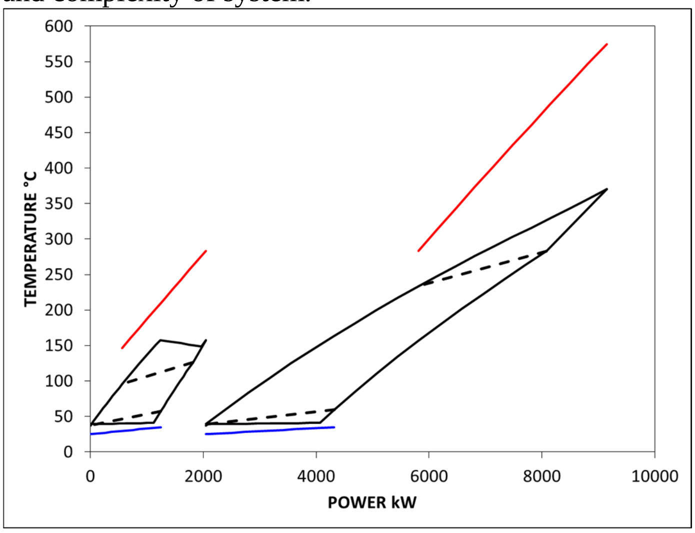

Figure 7 - Q-T diagram for enhanced ORC bottoming solution

Table Ⅰ: Preliminary data for power-only operation

			Standard ORC	Enhanced ORC
Gasifier	**Fuel power input (rel. To NCV)**	**kW**	**8362**	**8362**
	NCV fuel (moisture content wood chips 27.5 wt.% w.b.	*kJ/kg w.b.*	12701	12701
	Fuel input	*kg/h*	2370	2370
	Ash	*kg/h*	9,5	9,5
	NCV producer gas (gasifier outlet)	*kJ/kg w.b.*	5100	5100
	Temperature producer gas out of gasifier	*°C*	400	400
	Total power outpu gasifier	**kW**	**8224**	**8224**
	Heat losses producer gas	**kW**	**8**	**8**
	Temperature producer gas after heat loss	*°C*	*396*	*396*
Gas Turbine	**Total power input turbine**	**kW**	**8216**	**8216**
	Pressure producer gas into turbine	*barg*	*14*	*14*
	Mass flow producer gas into turbine	*kg/s*	*1,47*	*1,47*
	Mass flow air into turbine	*kg/s*	*8,73*	*8,73*
	Electric power output turbine - gross	**kW**	**2054**	**2054**
	Thermal power exhaust gas out of turbine	**kW**	**5916**	**5916**
	Mass flow exhaust gas	*kg/s*	*10,2*	*10,2*
	Temperature exhaust gas out of turbine	*°C*	*575*	*575*
	Heat losses exhaust gas	**kW**	**36**	**36**
	Temperature exhaust gas into ORC	*°C*	*572*	*572*
ORC	**Thermal power input ORC - from exhaust gas**	**kW**	**4284**	**4906**
	Thermal power input ORC - from cooling PG	**kW**	**-**	**-**
	Conversion losses ORC	**kW**	**27**	**27**
	Electric power output ORC - gross	**kW**	**966**	**1328**
	Thermal power output ORC (not used)	**kW**	**3291**	**3705**
Heat recovery	*Temperature exhaust gas out of ORC*	*°C*	*197*	*129*
	Low-temperature heat recovery exhaust gas (used)	**kW**	**-**	**-**
	Temperature exhaust gas leaving heat recovery	*°C*	*197*	*129*
	Heat content exhaust gas rest (not used)	**kW**	**1632**	**1010**
	Ambient temperature	*°C*	*15*	*15*

Table ⅠⅠ: Preliminary performance data for power-only operation

			Standard ORC	Enhanced ORC
Overall plant	**Total electric power output - gross**	**kW**	**3020**	**3382**
	Auxiliary power consumption gasifier plant	**kW**	**82**	**82**
	Auxiliary power consumption air cooler	**kW**	**11**	**11**
	Auxiliary power consumption gas turbine	**kW**	**16**	**16**
	Auxiliary power consumption ORC	**kW**	**43**	**93**
	Auxiliary power consumption pumps	**kW**	**10**	**15**
	Auxiliary power consumption compression (air, producer gas)	**kW**	**281**	**281**
	Total electrical power output - net	**kW**	**2577**	**2884**
	Total utilized thermal power output	**kW**	**-**	**-**
	Total electric efficiency - gross	**%**	**36,1**	**40,4**
	Total electric efficiency - net	**%**	**30,8**	**34,5**

Table III: Load case data for power only module		**Standard ORC**	**Enhanced ORC**
Net thermal power processed by ORC	**kW**	**4270**	**4906**
Exhaust gas temperature into ORC	**°C**	**575**	**575**
Exhaust gas temperature out of ORC	**°C**	**197**	**138**
Total exhaust gas flow rate	**kg/s**	**10,2**	**10,2**
Exhaust gas average heat capacity	**kJ/kgK**	**1,1**	**1,1**
Heat losses (on gas-fluid exchanger)	**%**	**-**	**-**
ORC overall net output	**kW**	**920**	**1237**
Thermal power to cooling source	**kW**	**3280**	**3607**
Average air temperature (Dry bulb)	**°C**	**15**	**15**
Cooling water inlet temperature	**°C**	**23**	**23**
Cooling water outlet temperature	**°C**	**35**	**31**

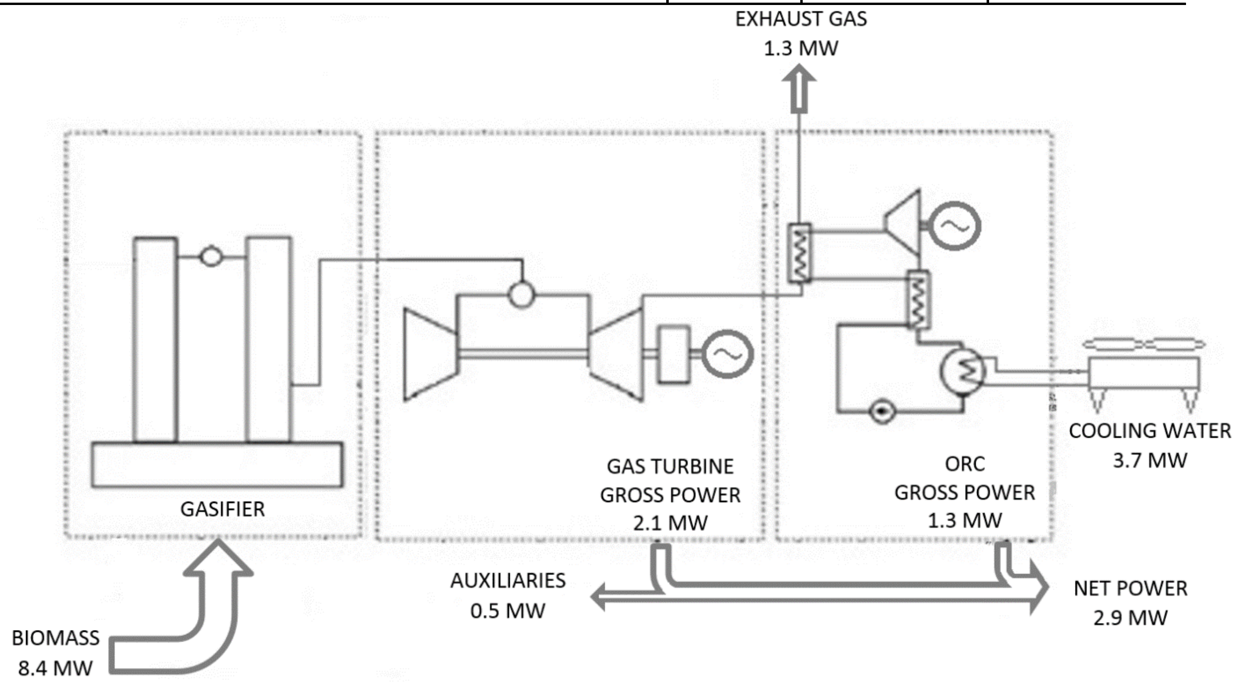

Figure 8 – Simplified block diagram and performance

6. CONCLUSIONS AND FINAL REMARKS

The solution outlined here would allow to obtain a plant, well adapted to converting wood biomass to electric power in the few MW power range, featuring some very attractive points:

- A high overall efficiency of conversion, around 30% for a power-only system with standard ORC.
- Low pollutant content of the exhaust gases.
- Fast modulation of power produced, which could become an important feature for a stand-alone unit.
- Good tolerance concerning the characteristics of the biomass fed to the gasifier, similar to the one of an updraft gasifier.
- Performance with an ORC bottoming system featuring very high temperature supercritical cycle could exceed 34%.

Up to now the solution has been the subject of a number of studies and preliminary evaluations, the technical feasibility, expected performance and cost effectiveness shall be ascertained in the frame of the future activity. If the expected results are confirmed, the proposed solution could give an important contribution to spreading the practical use of small scale biomass sources for power, (typically around 5 MW of electric power produced, by adopting two OPRA Gas Turbine units in parallel), all around the world.

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APPENDIX I- Description of the TWINGAS concept.

With reference to figg.2 and 9, the proposed gasifier is composed of at least two reactors (vessels 1, and vessel 2) and two connecting vessels or ducts, the hot side duct 3, and the cold side duct.
Biomass feed (wood chips, or any other biomass of interest) are fed through the gated feed mechanisms 5 and 6, and flow down in the twin vessels to the high temperature zone at the bottom. The biomass is pyrolyzed to char in zone 7. In the subsequent zone 8 the char reacts with the volatiles generated in the pyrolysis and air from the top air feeds 9,10 (if present) to produce syngas.
The syngas is extracted through ports 11, 12 in the vessels, or through port 13 in the bottom duct. The charcoal column is retained by grates 14, 15 while the ash falling to the bottom of the bottom duct 3 is extracted by a suitable mechanism 16 (screw or other mechanism).
The temperature of the gas in the bottom duct 3 is held at the value required for proper reaction within the vessels by a burner 17, introducing in the gas the correct amount of oxidizing agent (air, oxygen or any oxygen containing gas). The temperature set is one of the main variables in gasifier operation, in principle it should be as high as possible without exceeding the ash melting threshold.
The whole system is characterized by the pumping device 18, a fan which pushes alternatively the gas in the vessel 1 towards the vessel 2 and viceversa. As the head loss through the biomass columns is low compared to the average pressure of the gas, the pumped gas will behave as a nearly incompressible fluid , and a substantially alternate flow of gas will be established throughout the whole system.
This alternate flow involves that the high temperature at the bottom is easily transferred by the flowing gas to the reacting char bed in the twin vessels, thus supplying the required energy for the gasification reactions.
The following advantages are expected from the alternated flow in the two vessels: each vessel is operated, for about half time, as an updraft gasifier. In this phase a gas flow is established from the high temperature zone to the pyrolysis zone and, further up, to the drying zone. This phase allows an effective transfer of heat to the colder zones following a substantially counter-flow scheme. The gas exiting the top layer of biomass of this "updraft" gasifier, is not sent to utilizer, on the contrary it flows through the other vessel, acting in this phase as a "downdraft" gasifier. Flowing down, the gas becomes loaded with steam from the drying section and then with tar, from the pyrolysis zone. It gets progressively at higher temperature, taking heat from the layers it

goes through. It transfers steam and tar to the char bed, where they participate to the gasifying reactions.
Tars are decomposed in the bed, CO and H_2 levels are enriched: the typical effects of a downdraft scheme.
In order to have this scheme running sustainably, an energy input is required as well as an extraction of the useful product, syngas. Like in most gasifiers, fresh energy is supplied by introducing a sub-stoichiometric amount of oxidizer, typically air, or oxygen-enriched air. A number of different options are possible concerning the site of introduction, the most obvious position being the connecting drum at the bottom of the two vessels. In this area the temperature is high, typically around 800 °C, in order to achieve fast going reactions in the char bed, while avoiding ash softening. Introduction of the oxidizer in this area involves the development of immediate reaction with the gas and allows a good control on the temperature in this area, too.
Extraction of produced gas is more tricky, as it should be extracted in a low tar content zone. Also, the temperature should not be too high, to reduce the duty of the heat exchanger preheating of the oxidizer. A position along the two vessels, corresponding to the lower half of the char bed is most probably the best solution. However, due to the pressure drop within the bed, the gas will preferably flow out from the "downdraft" vessel. Hence a gas with a good combination of tar removal and temperature should be obtained. An alternated extraction, controlled by a valve or a fan, can give a number of interesting control strategies.

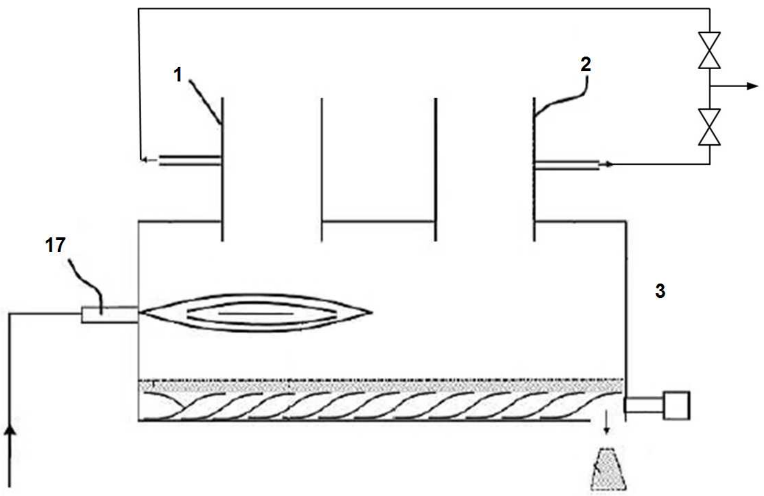

Figure 9 - Extraction points and control values for syngas in Twingas gasifier

In summary, the Twingas solution is expected to allow an effective combination of the advantages of both updraft and downdraft fixed bed gasifiers: moreover so, as it gives new tools for controlling the process, that is the frequency and the intensity of the alternate flow, which are independent from the flow of oxidizer.
Moreover it can be expected that, by keeping a larger thickness of char bed at high temperature, the Twingas solution should allow a much faster modulation of load, and in particular a much faster load increase after an extended low load period. This aspect can be very important for systems supplying an isolated grid.
The Twingas solution has been here summarized, its analysis is in fact complex and involves a time dependent simulation, much more demanding than the already complex simulation of conventional gasifiers.