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Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2003 217: 519
DOI: 10.1243/095765003322407566

IPRP (Integrated Pyrolysis Regenerated Plant): gas turbine and externally heated rotary-kiln pyrolysis as a biomass and waste energy conversion system. Influence of thermodynamic parameters

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Abstract: Sustainability is one of the main goals to achieve in order to guarantee a future for future generations and requires, among other issues, the recourse to renewable energy sources and the minimization of waste production. These two issues are contemporarily achieved when converting waste and residual biomass into energy.

This paper presents an innovative concept for energy conversion of the abovementioned residual fuels; it combines a rotary-kiln pyrolyser, where the residual energy sources are converted into a medium lower heating value (LHV) syngas, with a gas turbine that produces energy, and also provides waste heat to maintain the endothermic pyrolysis reaction. Byproducts of the reaction include char and tars that have an interesting energetic content and may also be used to provide supplementary heat to the process.

Through software modelling the paper analyses the influence on performance of main thermodynamic parameters, showing the possibilities of reaching an optimum for different working conditions that are characteristic of different sizes of gas turbines. This is interesting both for medium-to-big size power plants, where the IPRP efficiency is comparable to a grate-based incinerator, but at lower investment costs, and in the micro-small scale, for which there is no available technology on the market.

Keywords: biomass, solid waste, pyrolysis, simulation

NOTATION

B&W	biomass and waste
CC	combustion chamber
COMP	compressor
CYCLO	cyclone
GT	gas turbine
ICE	internal combustion engine
LHV	lower heating value
P	pressure (Pa)
PYRO	pyrolyser
Q	heat ($\mathrm{kJ/kg_{rdf}}$)
RDF	refuse derived fuel
RF	residual fuel
SCR	scrubber
SYN	syngas
T	temperature (K)
TE	tar energy [from residual tar (char) combustion] ($\mathrm{kJ/kg_{rdf}}$)
TIT	turbine inlet temperature (K)
β	compressor ratio
ϕ	Specific additional fuel consumption ($\mathrm{kg_{NG}/kg_{RF}}$)

Subscripts

air	air
ext	external
in	referred to the input of a generic system
NG	natural gas
P	pyrolysis
rdf	refuse derived fuel
RF	residual fuel
syn	syngas

The MS was received on 16 September 2002 and was accepted after revision for publication on 16 May 2003.

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1 INTRODUCTION

Turning waste and/or biomass into energy is addressed as one of the key issues for reaching sustainability and to meet the ambitious goals of the Kyoto Protocol [**1**]. Bioresidues and wastes show null or small CO_2 emission balance when converted into energy, as well as a lower overall environmental impact, when compared to their landfilling.

Nevertheless available and mature technologies for power production are mostly grate-based incineration plants with heat recovery and steam production for turbine expansion. This limits both the overall plant efficiency (around or below 25 per cent) and the minimal size economically convenient (above 2 MWe).

More efficient solutions may be obtained through combustion optimization (fluidized bed) or by turning the residue into a medium–low LHV gas through direct (incomplete combustion) or indirect (external heat) thermal degradation and biodegradation (digestion). The syngas obtained may then be utilized as a fuel for medium–high efficiency internal combustion engines (ICE) based power cycles or gas turbine (GT) based combined cycles. Many different gasification techniques are available but their technical and economical feasibility is still at a demonstration level, especially for the small and microscale fields. On this size the gasifier could easily be connected to ICEs, therefore reducing the optimal size of the plant for economical feasibility. Characteristics of some major installation are listed in Table 1.

This study presents an innovative solution for waste and/or biomass energy conversion by coupling a rotary-kiln, externally heated waste pyrolyser (PYRO) to a GT fuelled by the pyrolysis gas produced from the thermal degradation of residual fuel (RF). The cycle is addressed as a regenerated one because waste heat from the GT is returned to the PYRO, providing part of the energy required for thermal degradation of the RF. The eventual residual energy is provided by char or tar combustion, which are byproducts of the pyrolysis process with an interesting LHV. Pyrolysis was preferred to gasification because, being an old and well-known process [**4–15**], it also provides a higher LHV gas, and char and tar as byproducts that may be reused in the process.

An efficiency evaluation and optimization of the plant was carried out by varying the main thermodynamic parameters in order to identify the best performing arrangement with respect to the possible size of the plant. The results show interesting efficiencies obtainable for every plant scale considered, even for the micro-scale, where no existing solution is available, and, moreover, higher performances with respect to the state of the art (SOA), making IPRP technology competitive with traditional incineration techniques [**16–18**].

2 PLANT DESCRIPTION

The plant layout analysed in the present work is presented in Fig. 1. A generic RF is fed through a hopper to the rotary-kiln pyrolyser (PYRO) built as a cylindrical tube in a tube heat exchanger. The inside rotating cylinder is the reaction chamber where the thermal degradation to syngas, char, and tars of the RF is achieved, in the absence of oxygen. The indirect heating of the residue results in a higher LHV of the syngas, when compared to other gasification processes. The heat required to maintain the pyrolysis process is provided by hot gases circulating in the hollow space between the two cylinders from the GT exhaust. The temperature may be increased, if necessary, by burning part of the char and tars generated during pyrolysis in the tar combustion chamber (TAR CC) or also an external fuel.

Syngas at high temperature from the pyrolyser is cooled, to condense tars and water, and cleaned in a wet scrubbing section (CYCLO + SCR), to eliminate aggressive compounds that may damage the gas compressor and the turbine itself. The fuel gas is then compressed (COMP SYN) and injected into the GT combustion chamber (CC).

The energy required for syngas compression reduces slightly the overall power output and increases as the compressor ratio (β) increases [**16–18**]. Exhaust gases leaving the pyrolyser are conveyed to the stack after a second cleaning section and a dry filtering section (CYCL + SCR + FILTER) to ensure that emission limits are respected.

3 OBJECTIVES

An efficiency evaluation and optimization of the plant was carried out by varying the main thermodynamic parameters in order to identify the best performing arrangement with respect to the possible size of the plant. In particular three main objectives can be isolated.

The first objective of the study is to determine the efficiency of the IPRP plant as a function of its main design variables [GT compression ratio (β), turbine inlet temperature (TIT), and pyrolysis temperature (T_p)] and to point out their influence on plant performance and their mutual interference. Some typical expected results are as follows.

Table 1 Biomass to energy conversion plant efficiencies [**2, 3**]

Technology	Building status	Fuel	Plant capacity (MW)	Efficiency (%)
Travelling Grate Average Zurn/NEPCO	Existing	Wood	25	29
Travelling Grate McNeil (USA)	Existing	Wood	50	30
Circulating Fluidized Bed Händelőverket CHP (S)	Existing	Wood	46	32
Bubbling Fluidized Bed Deluano I plant (USA)	Existing	Agr. waste	27	29
Vibratine Grate Enkőping (S)	Under construction	Wood	28	33
IGCC Värnamo (S)	Existing	Wood chips	6	32

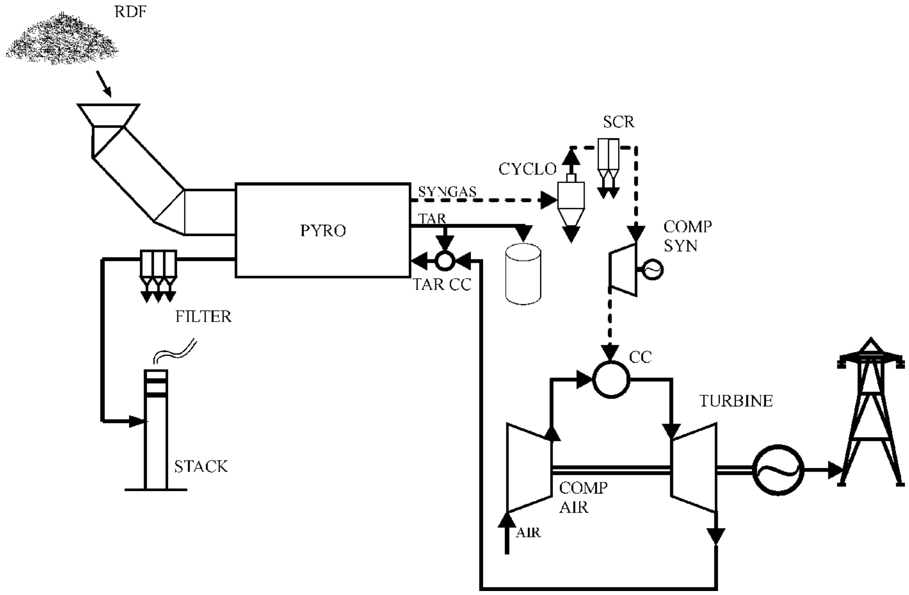

Fig. 1 Plant layout

- An increase in β will increase the GT efficiency, but not necessarily the overall plant efficiency, because the work required to compress the syngas produced will also increase.
- A similar conclusion may be obtained when discussing an increase in the TIT or in T_p, because both solutions yield more syngas from the RF pyrolysis but also require more heat to be provided by tar or external fuel combustion.

The contemporary effect of the three parameters will have to be discussed, to indicate the best solution in terms of overall plant efficiency.

The second objective of the study is to determine the values of the above-described variables that yield best IPRP overall efficiency and to compare it to the SOA.

The third objective of the study is to evaluate the compatibility of these values with different sized commercial GT design values in order to evaluate the feasibility and scalability of the IPRP.

4 METHODOLOGY

The overall plant performance was determined, through software modelling, as a function of three design variables, namely β, TIT, and T_p, which were varied over an adequate range and with an adequate step as described in Table 2. Specific work, plant efficiency, and residual energy available from tar and char production are the results that will be considered and discussed.

Table 2 Parameterization of the simulations

Parameter	Range	Step
Pyrolysis temperature (T_p)	823–1123 K	100 K
Compression ratio (β)	2–30	1
Turbine inlet temperature (TIT)	1000–1500 K	100 K

Plant modelling was carried out using home-made software [**18**] that utilizes thermodynamic relations, energy balances, and data available in literature. This approach was preferred to proprietary software for economical reasons and because the power plant simulation software that is commercially available also requires a major user effort to define not-off-the-shelf components such as a pyrolysis reactor. The home-made software utilizes data from literature and well-known thermodynamic relations that justify a high degree of confidence in results. The software will, however, be tested on data from a real plant and eventually made available.

4.1 Pyrolysis reactor modeling

The reactor was simulated in the steady state and no transient or kinetic behaviour is considered either for heat transfer or pyrolysis reaction. The equilibrium temperature, where reactor, pyrolysis products, and exhaust gases to stack are assumed, is the pyrolysis temperature T_p.

Pyrolysis products percentages and LHV, as a function of pyrolysis temperature, were obtained from data available in the literature and in particular for plastic waste (composition shown in Table 3) pyrolysed in an externally heated laboratory-scale rotary-kiln pyrolyser [**19**]. The yield of pyrolysis products is shown in Fig. 2.

Table 3 Primary analysis and ultimate analysis of the raw materials (dry air basis) [**18**]

Proximate analysis (wt%)		Ultimate analysis (wt%)	
Moisture	0.17	Carbon	89.28
Ash	0.06	Hydrogen	13.66
Volatile matter	99.77	Nitrogen	0.06
Fixed carbon	0	Sulfur	0.02
		Oxygen	0
		LHV (kJ/kg)	34 440

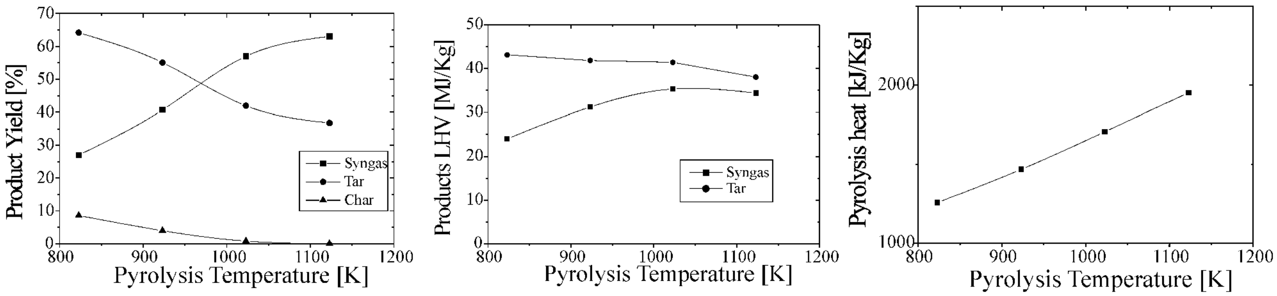

Fig. 2 Pyrolysis products yield (left) [**16**] and HHV (centre) [**16**] and heat required for pyrolysis [**17**]

As different residues behave in different ways when heat is provided, the data utilized may only be representative of a high plastic content residue as RDF can be, with insignificant char production when compared to tar production (Fig. 2). However, different residues may yield different pyrolysis products, but the energy balance shall be maintained, therefore lower tar production usually results in higher char production (that is, biomass) and vice versa.

An assumption is made that because in this study we are interested only in char/tar energy content (and not in their composition), every reference to tar energy is assumed to be extendable to char energy, therefore the results obtained may be generalized to any RF, as far as trends are concerned. This assumption is confirmed when considering biomass, which pyrolyses mainly to char. Therefore, from now on, every reference to tar will also be extended to char if considering an RF that pyrolyses mainly to char and syngas (that is, biomass).

The energy required for pyrolysis was assumed to be the sum of different contributions obtained [**20**] for rubber, the behaviour of which was considered coherent with the results [**19**] for plastic waste, because heat capacity and heat of reaction are similar. This methodology yields results that are coherent and comparable to the results obtained equalling endothermic and exothermic reactions for biomass [**21**].

The different energy contributions are:

1. heat capacity of the feedstock to the reaction temperature considered [**20**];
2. vaporization energy of pyrolysis reactants [**20**];
3. heat of reaction [**20**];
4. heat capacity of products to the T_p.

The only item that is sensibly dependent on T_p is the last.

4.2 Other components modeling

An energy balance in the pyrolyser was used to estimate the additional energy required to increase GT exhaust gases temperature to T_p by tar or external fuel combustion. Char LHV was not considered, assuming that the small yield would not be significant for final results.

The GT, compressor, and heat exchangers were simulated according to ideal conditions while irreversibilities were introduced through efficiencies as described in Table 4, which also shows other technical assumptions of the simulation.

4.3 Exclusions

The state of the art for tar combustion and eventual problems will not be discussed in the present paper. The gas treatment section analysis will also be neglected, assuming that syngas is cooled to 50°C in the scrubber and that the entire fraction of water vapour is condensed. Also, no consideration is made for acid vapour treatment and eventual dioxin production and abatement. These issues represent the technical barriers of the IPRP technology and will be discussed in other works.

Finally, the GT combustion chamber, usually designed for conventional fuels, will require some adaptation, especially in the fuel injection nozzles, because of the low LHV fuel gas [**22**], but they are not analysed in the present work.

4.4 Normalization

The analysis was carried out referring all mass and energy flows to 1 kg residue in input, which yields a different syngas production rate depending on T_p (Fig. 2). With this approach the higher the syngas production, the higher the GT power output, but also the work required for its compression to GT CC operational pressure, with this latter a function of β.

Table 4 Technical assumption used in the simulation

	Parameter	Value
Air	$P_{air,in}$	101 325 Pa
	$T_{air,in}$	288 K
Syngas	$P_{syn,in}$	101 325 Pa
	$T_{syn,in}$	323 K
Efficiencies	Air compressor	80%
	Syngas compressor	80%
	Turbine	90%
	Combustion	98%
	Tar combustion	90%
	Pyrolyser heat exchange	90%
Pressure losses	Combustion chamber	5%
	Fuel injection nozzle	3%

5 DISCUSSION

5.1 Specific work

We will consider in the following the specific GT work as the work produced by the GT when it is fuelled by the quantity of syngas obtained from the pyrolysis of 1 kg of RF; the specific syngas compression work is the work required to compress the amount of syngas produced by 1 kg of RF pyrolysed from ambient pressure to GT CC pressure. Therefore, the GT specific work is referred to 1 kg of residue fuelled to the plant and not, as usual, to 1 kg of working fluid. This means that the air mass flow considered in the GT analysis is the quantity necessary to burn the syngas produced by the pyrolysis of 1 kg of RF, given a value of the air/fuel ratio.

For a better understanding of the dependence of the IPRP efficiency on the main variables, Fig. 3 shows the specific GT and syngas compression work as a function of β considering two different values of TIT and T_p.

5.1.1 Effect of TIT

Increasing TIT, with reference to Fig. 3, while maintaining T_p constant, results in a slight increase of the GT work because the area inside the Joule cycle has increased (curves II and III). No modification in the syngas compression work is experienced (curves V and VI) because syngas production does not vary when keeping T_p constant.

5.1.2 Effect of β

With reference to Fig. 3, an increase in β produces, as a well-known effect, an increase in the GT work with a decreasing slope as β increases. The slope inverts its sign at low values of TIT, therefore the GT specific work may decrease for high values of β (curves I and III) while the slope maintains a positive sign at high values of TIT (curve II).

5.1.3 Effect of T_p

The effect of varying T_p, with reference to Fig. 3, is a consequence of the different yield of pyrolysis products. In particular, an increase in T_p results in a higher syngas rate of production (Fig. 2), therefore more fuel available: the GT specific work is increased (curves I and III) as well as the syngas compression work (curves IV and VI).

5.2 Efficiency

Plant efficiency is defined as the ratio between the net power output of the plant and the energy provided with the residual fuel and eventually with natural gas:

$$\eta = \frac{\text{specific work (GT} - \text{COMP}_{\text{syn}})}{\text{LHV}_{\text{RF}} + \phi\text{LHV}_{\text{NG}}} \tag{1}$$

Results are shown on six different graphs: one for each value of TIT considered (Fig. 4). Each graph was obtained by plotting both plant efficiency (continuous lines on lower part of graph and left side scale), and tar residual energy (dashed lines on upper part of graph and right side scale) versus the β of the GT. (Note: Negative values for tar residual energy indicate the amount of energy required from an external fuel.) Finally different symbols are representative of different T_p as described in the legend of Fig. 4.

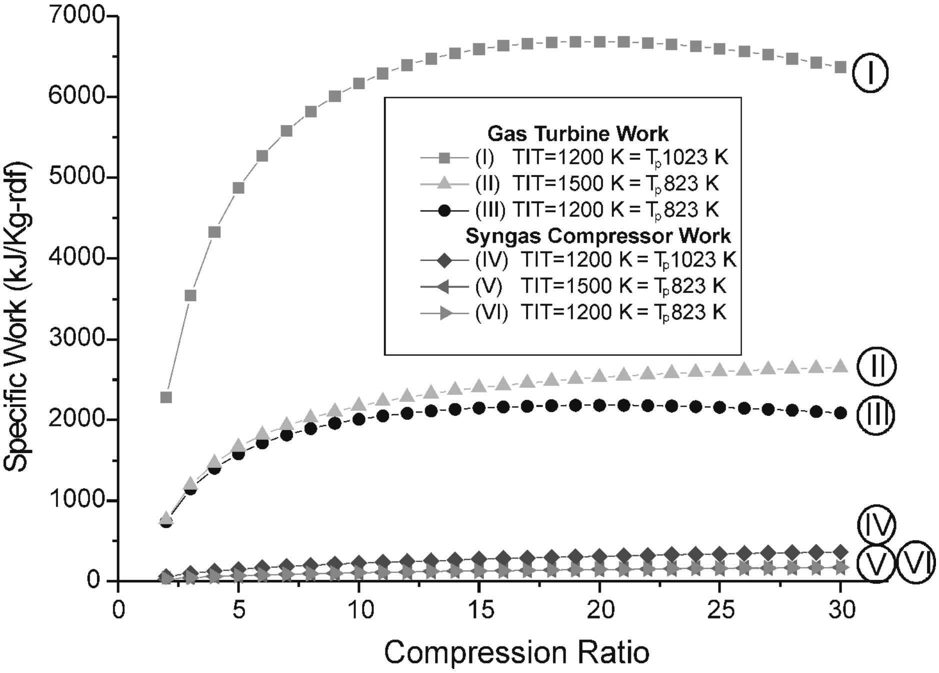

Fig. 3 Effect of TIT and T_p on specific work

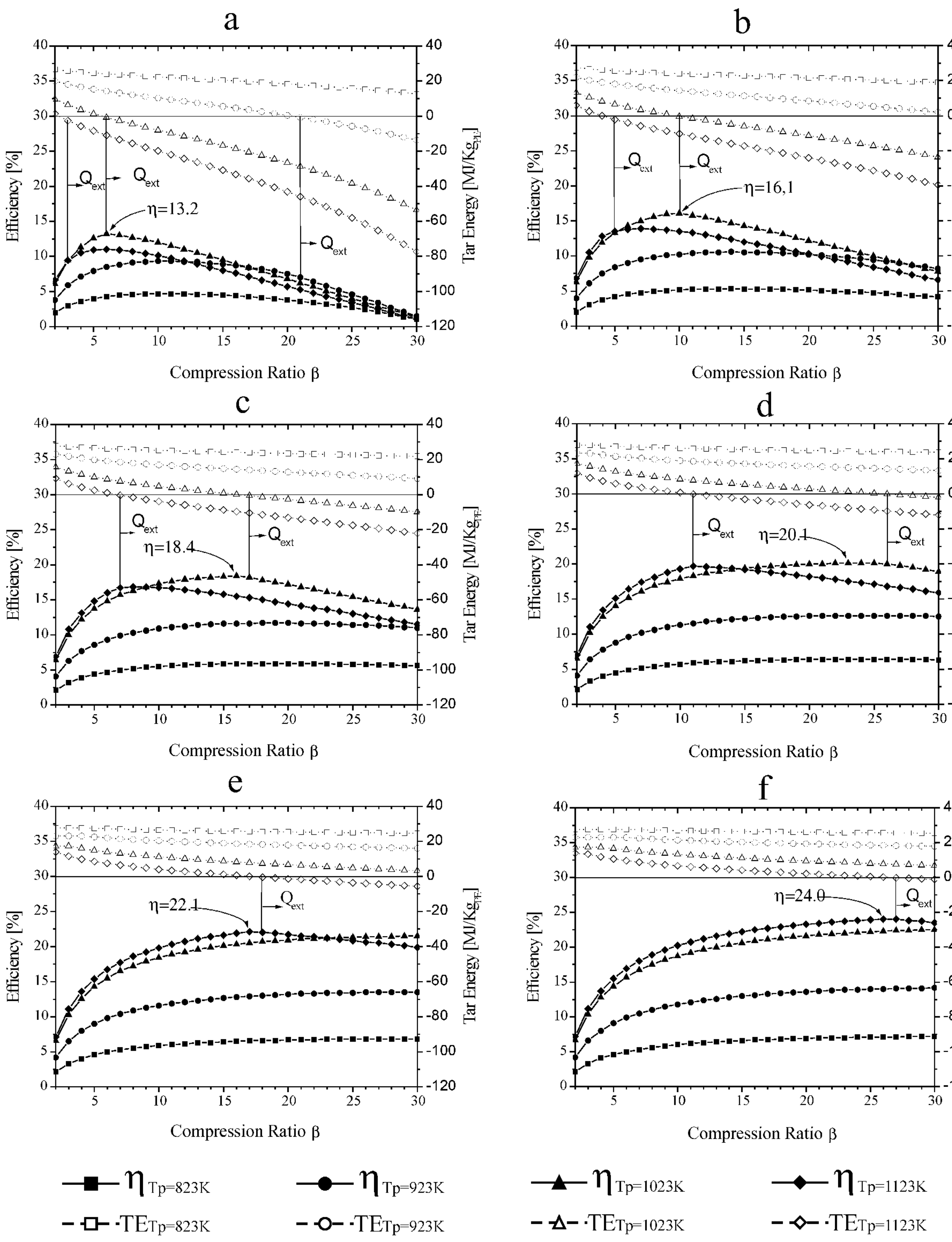

Fig. 4 Plant efficiency depending on the main functional parameters

5.2.1 *Byproduct contribution*

With regard to efficiency, the previously described interaction between thermodynamic parameters has also to deal with the heat required to maintain the pyrolysis process. Tar production depends on pyrolysis temperature (Fig. 2), which is slightly lower than the gas temperature at the TAR CC outlet. Therefore the higher the pyrolysis temperature the higher the quantity of tar (char) to be burnt to increase GT exhaust gas temperature to meet pyrolysis temperature. Moreover, the higher the pyrolysis temperature, the lower the tar production (Fig. 2); therefore there will be cases in which tar combustion is not sufficient to increase GT exhaust gas temperature to the value required for pyrolysis, and an additional fuel (methane) will be necessary.

The eventual integration of an external fuel will be indicated by a negative value of available energy for tar (char), on the graphs of Fig. 4. This also means that the plant is not self-sufficient. On the other hand, some cases will show an excess of tar production with respect to the quantity required for pyrolysis; therefore the residual tar production will be considered as a positive value of available energy. In this case the plant is auto-sufficient and is also byproducing quantities with an interesting energy content (tar or char).

5.2.2 Effect of β

Consider first the results starting from the highest TIT, therefore referring to Fig. 4f. The efficiency is increasing with β, following the usual trend for a GT while an increase in T_{p} produces a vertical shifting of the curves towards higher values of efficiency because of the increased syngas production.

On the other hand, tar energy (TE) available from the residual tar (char) combustion decreases with β, because GT exhaust gas temperature is also decreasing with β; therefore more tar (char) has to be burnt to reach T_{p} and less residual energy is available. An increase in T_{p} shifts the curves towards lower values of TE because pyrolysis products are shifted towards syngas rather than tar (char) at high T_{p} (Fig. 2).

These two negative effects on TE may produce a null value for TE that is experienced for the highest value of T_{p} considered (1123 K), and at high β ($\beta > 26$). From this point the gap between GT exhaust gas temperature and T_{p} is too high to be covered with tar (char) combustion [also because tar (char) production is low]. Therefore additional heat is required from an external fuel and this lowers sensibly the plant efficiency and introduces a discontinuity in the trend.

5.2.3 Effect of TIT

Decreasing TIT (starting with Fig. 4f and moving to Fig. 4a) results in a general deterioration of performance with lower efficiencies and lower TEs; therefore all curves are shifted down with respect to Fig. 4f. The down-shifting of curves at decreasing TIT results in null values of TE for lower values of β (Fig. 4e, $\beta = 18$) and also for lower values of T_{p} (Fig. 4d, $\beta = 11$, $T_{\mathrm{p}} = 1123$ K and $\beta = 26$, $T_{\mathrm{p}} = 1023$ K, and so on).

The above-described null values of TE determine discontinuities in the efficiency trends that may produce overlapping curves when decreasing TIT. Therefore the highest T_{p} does not necessarily result in the highest possible efficiency, but it is to be noted that when decreasing TIT, the maximum efficiency is obtained for lower values of β.

This particular plant behaviour makes the integration of pyrolysis technology with GT interesting and suitable at every scale because a maximum efficiency point is obtainable over the entire range of variables.

5.2.4 Effect of T_p

Considering the effect of pyrolysis temperature, it can be noted that high values usually yield higher efficiencies, as long as the tar production is enough to maintain the pyrolysis process.

Curve overlapping caused by insufficient tar production, as described above, may return lower efficiencies for lines referred to high pyrolysis temperature but it is always confirmed that a maximum efficiency point is obtainable for a pyrolysis temperature of 1023 K or 1123 K. This latter point is also evident in Fig. 5 as explained hereafter.

5.3 Scalability

As stated earlier, IPRP technology appears to be suitable for every GT scale because best plant efficiency points are obtainable for high TITs at high β and low TITs at low β and these combinations match respectively big scale GT and small scale GT working conditions. Figure 5 shows the best efficiency points obtained at operational parameters typical of three different GT size.

For *micro-turbines*, results are shown for a low value of the compression ratio ($\beta = 4$) and low values of TIT (1000/1200 K). *Medium-sized gas turbines*, were characterized with $\beta = 12$ and mid values for TIT (1200/1400 K) while for *large-sized gas turbines*, results are shown for high values of the compression ratio ($\beta = 20$) and of TIT (1300/1500 K). The pyrolysis temperature considered is always the one that gives the best efficiency.

The compatibility of the values obtained at best efficiency points for commercial GT operational parameters at different sizes is accordingly demonstrated:

- For large-scale heavy duty GTs, best efficiency reaches 23.3 per cent at TIT = 1500 K and $\beta = 20$.
- For a medium-scale aero-derivative, typical efficiency is approximately 17.9 per cent at TIT = 1200 K and $\beta = 12$.
- For micro-turbines, typical efficiency is approximately 12.8 per cent at TIT = 1100 K and $\beta = 4$.

Therefore, best efficiency points are always obtained for high values of T_{p}, as stated before, while efficiency increases with increasing compression ratio and for increasing TIT while keeping β constant. Pyrolysis technology coupled to GTs may therefore represent an interesting biomass and waste (B&W) to energy solution, particularly in the small and micro-scales (where it could be the only solution).

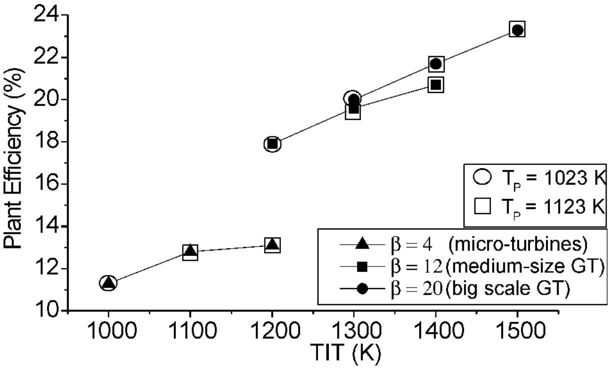

Fig. 5 Best plant efficiencies grouped for typical gas turbine parameters

6 CONCLUSIONS

An innovative biomass and waste to energy conversion system was proposed combining a rotary-kiln pyrolyser and a gas turbine. In the so-called Integrated Pyrolysis Combined Plant (IPRP), waste heat from the turbine is recovered in the pyrolyser to maintain the process while char (tar) firing may supply additional heat. A performance analysis for the IPRP was carried out by varying the main thermodynamic parameters, such as turbine inlet temperature, compression ratio, and pyrolysis temperature using home-made software and data available in the literature.

Uncertainties regarding calculation and methodology are mainly linked to the pyrolysis model and particularly to product yields and heat required to perform the reaction. They were assumed not to significantly affect the trends of the resulting curves (as demonstrated in ref. 21 when considering biomass). The efficiencies obtained may be considered significant of lower limits for the proposed technology because the values of single components' efficiencies were assumed in a conservative way.

The results show that best efficiency points are obtainable for combinations of parameters that are coherent with typical GT operation and for every GT size, therefore demonstrating the technical feasibility of the IPRP power plant using micro- to macro-sized GTs.

The efficiencies obtained are within the range of traditional grate-fired incinerators; therefore the uncertainties linked to the not yet mature technology (pyrolysis, gas cleaning) may be balanced by a better economical return, due to the lack of a steam cycle, making the IPRP an interesting alternative to traditional solutions for biomass and waste to energy conversion.

Moreover the interest may be enhanced for microscale units where no alternative for biomass and waste to energy conversion is available on the market for that size. The results show indeed that IPRP technology may be auto-sufficient when maintaining the pyrolysis process through char (tar) firing. Therefore IPRP provides an interesting solution for distributed generation on isolated areas, also considering the favourable conjuncture that microturbines are now experiencing.

Critical points of the proposed technology may be found in the variable yields and energy content of pyrolysis products, which may jeopardize performance and produce combustion irregularities. Also critical is the syngas cleaning section, which will guarantee optimal performance of the syngas compressor and of the GT. Similar uncertainties, however, are common to other concepts that still remain unproven such as externally fired biomass fuelled GT, or tar-based post-combustion in biomass and waste IGCC power plants. Gas cleaning is also an important issue common to every gasification plant based on an internal combustion engine.

Future work, already under study and to be published shortly, considers the possibility of further heat recovery from the pyrolyser outlet and through GT regeneration. This solution results in highly regenerative IPRP cycles, which achieve efficiencies comparable to biomass and waste IGCC cycles, but at a considerably lower cost, as stated above.

Also under study is the possibility of utilizing an ICE at a lower capital cost while also expecting lower efficiencies due to the lower availability of recoverable energy.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Professor J. M. Kenny for useful discussions on the DTA measurement technique and pyrolysis energy demand.

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