MODELLING OF WOOD WASTE FUEL CELL/GAS TURBINE FOR SMALL POWER GENERATION

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Abstract *– The use of small-scale combustion engine generators, especially, Diesel generators, fueled with gasified wood waste and pilot oil injection is an interesting option for powering sawmills and/or furniture industries. These systems are simple and low in cost, but due to its low global energetic efficiency (~20% at a small-scale plant) their use is economically justified only when the wood residue, for example, is produced in great quantity and at a low cost. However, with the purpose to search new technologies, since there are few alternatives available in Brazil, this paper presents an analysis of an alternative option that has good prospects for the near future – a distributed generation system consisting of a wood waste gasifier coupled to a fuel cell and a micro-turbine bottoming cycle. The study is based on the scale-up of a fixed bed, downdraft, stratified, open top, and internal gases recirculation gasifier, processing nearly 12 kg/h of Pinus Eliottii sawdust, coupled to a small (~150 kW) Solid Oxide Fuel Cell (SOFC) and a micro-gas turbine (~50 kW). This last equipment is derived from turbocompressors of supercharged reciprocating engines, added with a combustion chamber, recuperator and an electric generator, technologies apparently simple. With the aim of computationally reproduce the complete system, models based on the commercial simulation software "Cycle-Tempo" were conceived. The gasifier studied and the fuel cell were conceived based on equilibrium models. Although this strategy do not represent the reactions that occur at relatively high temperatures (~800°C) very well, these models can be used to show some tendencies on the global energy conversion of the system. A first analysis considers the fuel cell working with the gas produced in the gasifier built, whose chemical composition was an average of 10 tests (average cold gas efficiency of 62.8%). The results showed an energetic efficiency of 58.3% for the fuel cell/gas turbine power system. The analysis adopting a complex Cycle-Tempo model to the gasifier coupled to the fuel cell/gas turbine power system showed a global energetic efficiency nearly 37%.*

Keywords*: distributed generation, gasification, microturbine, fuel cell, biomass*

1. Introduction

A variety of options are applied today in the small power generation plants area (< 1 MWe). These options go from the use of fossil fuels (Diesel oil and natural gas) in generator groups and microturbines (already commercialized nowadays), passing through eolic generators, fuel cells working with hydrogen or natural gas (on initial phase of commercialization nowadays), and arriving up to the biomass gas generators. Diversifying the electrical energy production through different alternatives as those mentioned, is an important contribution to the distributed energy generation field.

The use of biomass as energetic in the three states: solid (wood, waste wood, forest and agroindustrial residues, etc.), liquid (ethanol, biodiesel, etc.), and gaseous (biogas and low Btu gas); has received attention of many people to the cogeneration of heat and power through small and medium plants. According to Purvis e Craig (1998), the use of biomass as an option to power generation must be stimulated specially to those applications where there is very high waste production, to avoid problems with environment disposal, and also, because it's a renewable energy source. Therefore, this is particularly interesting to both rural producers and agroindustrials, sawmills and furniture manufacturers. Today, in Brazil, the Federal Government stimulates the diversification of the national energetic matrix through PROINFA program (Programa de Incentivo a Fontes Alternativas de Energia Elétrica), which is coordinated by the Ministry of Mines and Energy (MME). The program establishes the contract of 3.300 MWe of energy to the National Interconnected System (SIN) distributed in three equal parts: small hydroelectric plants (PCHs), eolic, and biomass. This way, the Brazilian Government, making available part of the resources, acclaims different kind of companies to invest in the electrical energy generation through plant projects of small/medium size, applying one out of the three energetics mentioned.

In general, solid biomass, in special, wood, wood residues, sugar cane bagasse and rice husk, have been used directly in watertube steam boilers to cogeneration of heat and power with steam turbines. These plants, in general, present efficiencies that don't overcome values of 35% when producing only electricity. Another way for using biomass has gained interest throughout the world, mainly in Asian countries (Mukunda, *et el*., 1994; Chowdhury, Bhattacharya and Chakravarty, 1994), which is the gasification of biomass in small and medium reactors and the use of the fuel gas produced in internal combustion engines, particularly, in Diesel engines to power generation. The combination gasifier/engine is possible, since the fuel gas produced be cleaned to reduce undesirable chemical species such as Tar (< 100 ppm – Reed e Das, 1987) to a minimum. The integration of gasifiers with microturbines maybe causes fewer problems because these equipments can work with multifuels in the combustor. In the studies presented by Wander, Altafini and Barreto (2004) and Altafini, Wander and Barreto (2003), the results of performance of a small fixed bed type gasifier of wood residues (sawdust), downdraft, stratified and open top, are reported. This gasifier, whose capacity is around 12 kg/h, has an internal gas recirculation, where part of the gas produced is burned to raise the gasification reaction temperature (> 800°C). However, in the integration of the gasification process with Diesel engine, the plant global efficiency don't overcome 20%, and this type of application is only justified when there are big amounts of biomass available, such as wood residues, rice husk, etc.

The search for new technologies to improve the energetic conversion efficiency of the plants has led to the study of other types of integration. At this moment, a first family of microturbines (25 – 75 kW), second Massardo, McDonald and Korakianitis (2002), was launched on the distributed energy generation market, that presents levels of thermal efficiency varying between 28 and 30%, on the basis of state-of-the-art technology. Still, in accordance with Massardo, McDonald and Korakianitis (2002), at least ten manufacturers are involved in the development of microturbines. To maintain low costs, the configuration of the machines is sufficiently simplified, considering the following characteristics: (1) radial compressor with one stage; (2) radial inflow turbine of one stage; (3) electric generator directly coupled to the turbocompressor assembly of high speed and air cooled; (4) multifuel combustor (conventional or catalytic); (5) compact recuperator of high effectiveness; (6) simple control system; and (7) aerostatic bearing to support the shaft of the high speed turbocompressor assembly.

Another technology, which is gaining a lot of interest nowadays to attend the small users of energy, is the fuel cell. Based on the actual technology and due to its high cost, seems that it will take some years to be commercialized in large scale. Nevertheless, the integration of microturbines with high temperature fuel cell working at natural gas is able to get efficiencies of about 60% (Massardo, McDonald and Korakianitis (2002). This integration is possible because there is compatibility between the working parameters of both equipments, i.e., the exhaust gaseous effluents from Solid Oxide Fuel Cells (SOFC) with temperatures between 900 and 1.000°C are suitable to the inflow microturbine conditions. Also, the compressor discharge pressure at values of 4 bar is favorable to raise the SOFC power.

North American enterprises, supported by universities, developed several studies, like Fergusson, Fiard and Herbin (1996); Elangovan *et al.* (2001); Tharp *et al.* (1999); Hartvigsen, Khandkar and Elangovan (1999); Khandar, Hartvigsen and Elangovan (1999) and Kneidel *et al*. (2004). These studies report the performance/economic parameters of SOFCs, using different ceramic materials constituents of the electrodes (anode and cathode) and electrolyte. Other studies developed recently show the performance results of the SOFC/microturbine integration power plants: Cohn *et al*. (1998) and Kartha, Kreutz and Willians (2000). Particularly, this last study was the reason to the development of the work presented herein, because it predicts an interesting integration, which is the coupling of SOFC with microturbine, working with fuel gas produced in the gasification process to small scale power generation (< 200 kW) in rural areas. Therefore, on the basis of the results reported in Wander, Altafini and Barreto (2004) and Altafini, Wander and Barreto (2003), showed up the interest in reproducing the computational simulation made by Kartha, Kreutz and Williams (2000), to assess the technical viability of the wood residues integration, through the gasification process studied, with the SOFC and the microturbine. The Cycle-Tempo program (TNO, 1998) was used for the simulations, which has in its library of components the fuel cells with reformer included. The result of the thermal efficiency of the system studied was around 37%.

Although the fuel cell technology is still in wide maturation in developed countries, is understood that the study shown herein doesn't miss validity, since it's important to identify future alternatives able to contribute in some way to the distributed generation through systems of small, medium or even high energetic potential.

2. Power system conception

The energetic analysis deals with a small power plant composed by the integration of a fuel cell with a gas turbine to produce nearly 200 kW. As mentioned before, the fuel cell technology has a thermodynamic efficiency that may overcome 60% working with natural gas. According to Kartha, Kreutz and Williams (2000), other advantages of this technology is attracting great interest because it offers prospectively low capital cost, quasi-zero local air pollutant emissions, high reliability, and low operation and maintenance requirements. However, to the aim of this work, the fuel cell will be fed with low-BTU fuel gas produced in a wood residues (sawdust) gasifier. To attend the established power of 200 kW, around 1,400 kg/day will be needed to supply 12 hours of electricity per day to the factory. To meet this need of wood residue, the enterprise must be able to produce around 13 m^3 of wood per day, whose production is typical of a small producer.

The scheme proposed by the authors lastly referred considers the biomass being gasified and the fuel gas produced cooled and cleaned, which, along with air, are compressed (pressure ratio equal to 4.0) and preheated (both up to 552°C) in the gas turbine recuperator using heat recovered from the turbine exhaust. At the state-of-the-art technology of the microturbines commercialized, the compressor/combustor/turbine/recuperator assembly is mounted in the same framework. This means that the system must be modified, at first, to redirect air from the compressor to the fuel cell cathode, and to allow the preheating of the fuel gas too. At this point, is important to comment that the technology today available for vehicular turbocharger (passenger cars and trucks) is very similar to the compressor/turbine assembly of the microturbines with exception of the lubricated bearings and pressure ratio that doesn't overcome 3.0 at the truck engines. Therefore, to implement the gas power plant herein studied from vehicular turbocharger technology, it will be necessary to adapt the bearings and to install a combustor, a recuperator and to couple an electric generator. Independently of this, the simple scheme presented in Fig. 1 elaborated based on Cycle-Tempo™ software considers the following main characteristics: (1) a SOFC fuel cell fed with air on the cathode terminal, and fuel gas at the anode terminal; (2) both air and fuel gas are preheated in a recuperator (represented by two separated heat exchangers) by hot gases supplied from the exhaust of a gas turbine; (3) two compressors are coupled to the shaft of the turbine and feed the SOFC fuel cell with air and with cooled and cleaned fuel gas of wood residues gasification process, which passes through the recuperator; and (4) the gaseous effluent of the SOFC fuel cell are introduced into a combustor, whose outlet hot gaseous products fed the gas turbine.

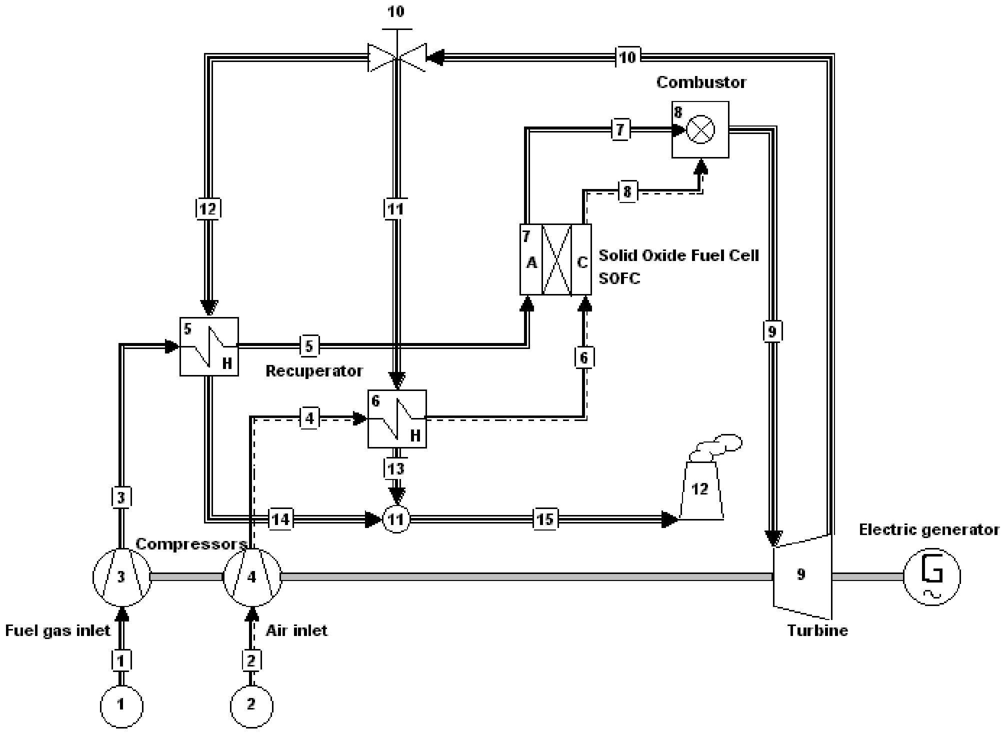

Figure 1 – Cycle-Tempo scheme of the biomass fuel cell/gas turbine integration

In the sequence, the main features of each component are shown.

2.1. Fuel gas conditions

The gasification process is an old technology used to convert, specially, a solid fuel in a low-BTU gas fuel. However, nowadays, there are sophisticated gasification technology working with several flow configurations in pressurized or atmospheric beds, and with pure oxygen or air as oxidant agent, and steam as moderated agent. There are still simple gasifiers that don't need high techniques for its construction.

The gasifier used in this analysis was a fictitious scale-up of that described in Wander, Altafini and Barreto (2004), where the biomass gasified in the tests was *Pinus Eliottii* sawdust and whose ultimate analysis (weight %) is: carbon = 52.00; oxygen (by difference) = 41.55; nitrogen = 0.28; hydrogen = 6.07; sulfur = 0.00; ash = 0.10; HHV = 20.407 MJ/kg, and LHV = 19.087 MJ/kg. The data used to analyze the scheme of the Fig. 1 were based on the average values of the experimental results of 10 tests performed and reported in Altafini, Wander and Barreto (2003): fuel gas composition (vol. %) – H_2 = 14.00, CO = 20.14, CH_4 = 2.31, C_2H_4 = 0.57, C_2H_6 = 0.14, CO_2 = 12.06, and N_2 = 50.79; HHV = 5,276 kJ/Nm^3; and cold gas efficiency ($\eta_{coldgas}$) = 62.86%. The fuel gas composition was assumed free of tar, particulates and alkalis, e.g., clean of any impurity.

2.2. Compressor conditions

Both compressors before identified operate with equal pressure ratios and the inlet pressures are nearly 0.93 MPa, which is the atmospheric local pressure where the power plant herein analyzed might be installed. The fuel gas compressor receives the composition stated above, and the other compressor receives normal air, e.g., at temperature of

25°C and 60% of relative humidity. The inlet mass flow rates are calculated by the solver system of the Cycle-Tempo program. The isoentropic and mechanical efficiencies of both compressors are fixed.

2.3. Recuperator parameters

In the two heat exchangers representative of the recuperator, the outlet temperature and the pressure drop ($\Delta p/p$) are established. Others values are obtained from remaining components. Cycle-Tempo program doesn't allow the fixation of the effectiveness of heat exchangers, but this parameter can be calculated from the resultant temperatures.

2.4. Fuel cell

Several studies were made focusing on high temperature fuel cell, especially about the SOFCs, as commented previously in this paper. Particularly for small applications, the solid oxide fuel cell seems to be more promising than the molten carbonate (MCFC), according to Kartha, Kreutz and Williams (2000), by the several advantages pointed out by these authors.

Typically, a tubular or planar SOFC presents its components (electrolyte, electrodes and interconnecting elements) mounted in modules (cell assembly), bundles (module assembly), strips (bundle assembly) and stacks (strip assembly), being this last arranged in a parallel arrangement to produce the entire assembly. The solid electrolyte operating at 650 to 1,000°C, the ionic conduction by oxygen ions takes place. According to Hartvigsen, Khandkar and Elangovan (1999), the SOFC works at sufficiently high temperature to embody an internal reformer. The effluent anode gases are sufficiently rich in high temperature steam to provide all needed water to the reaction of steam reforming, $CH_4 + H_2O \leftrightarrow CO + 3H_2$, and of the water gas shift, $CO + H_2O \leftrightarrow CO_2 + H_2$.

In the fuel cell Cycle-Tempo model, the chemical balances and the current density are based on the average cell temperature, e.g., the model is isothermal. In accordance to Fig. 1, the flow type of the fuel cell is co-flow, and in the design calculations, cell voltage, current density, fuel utilization [ratio between the number of mole H_2 (and CO) in the fuel cell and the number of mole H_2 – equivalent (maximum amount of H_2 that can result) in the fuel], and power, can be specified. Based on this data, the program calculates the corresponding cell resistance and all area. Therefore, the following parameters were specified: cell voltage, current density, fuel utilization, and net power. Other important data were fixed: fuel cell pressure drop ($\Delta p/p$), efficiency of DA/AC conversion, and outlet temperature anode and cathode.

2.5. Combustor and gas turbine conditions

According to Fig. 1, the combustor receives the hot exhaust gases (air and fuel gas) from the fuel cell. The program needed an estimate of the oxidant-fuel ratio for the first iteration and the program calculated the reaction temperature.

The main conditions attributed to the gas turbine are: pressure ratio, isoentropic efficiency, and mechanical efficiency. Moreover, the electric generator efficiency was fixed. The net (discounting compressor power) turbo-generator group power is calculated by the program.

Table 1 summarizes the main parameters specified in the analysis.

Table 1 – Main operation parameters

Parameter	Value	Parameter	Value
Gasifier cold gas efficiency	62.86%	Efficiency DC/AC conversion	96%
Compressor pressure ratio	4.0	Inlet temperature fuel cell	552°C
Compressor isoentropic effic.	80%	Outlet temperature fuel cell	800°C
Compressor mechanical effic.	99.5%	Fuel cell pressure drop, $\Delta p/p$	3%
Recuperator pressure drop, $\Delta p/p$	3%	Gas turbine pressure ratio	3.54
Net fuel cell power	150 kW	Inlet temperature gas turbine	900°C
Fuel cell voltage	0,7 V	Gas turbine isoentropic effic.	84%
Current density fuel cell	2,000A/m^2	Gas turbine mech. Efficiency	99.5%
Fuel utilization of fuel cell	0.85	Electric generator efficiency	94%

3. Efficiency result of the system

Figure 2 shows the scheme presented in Fig. 1 with all results obtained from Cycle-Tempo simulation. The total power produced by the plant was nearly 198.7 kW and its overall efficiency was calculated to be 58.7% based on the inlet fuel gas energy (338.7 kW on $LHV_{fuel\ gas}$ basis). With a cold gas efficiency in the gasification system of 62.86% (≈ 62.9%) considered in Table 1, the overall efficiency of the biomass gasification/fuel cell/gas turbine integration was of 36.9% versus 43.4% reported by Kartha, Kreutz and Williams (2000) assuming a cold gas efficiency of 79% at the authors' gasifier.

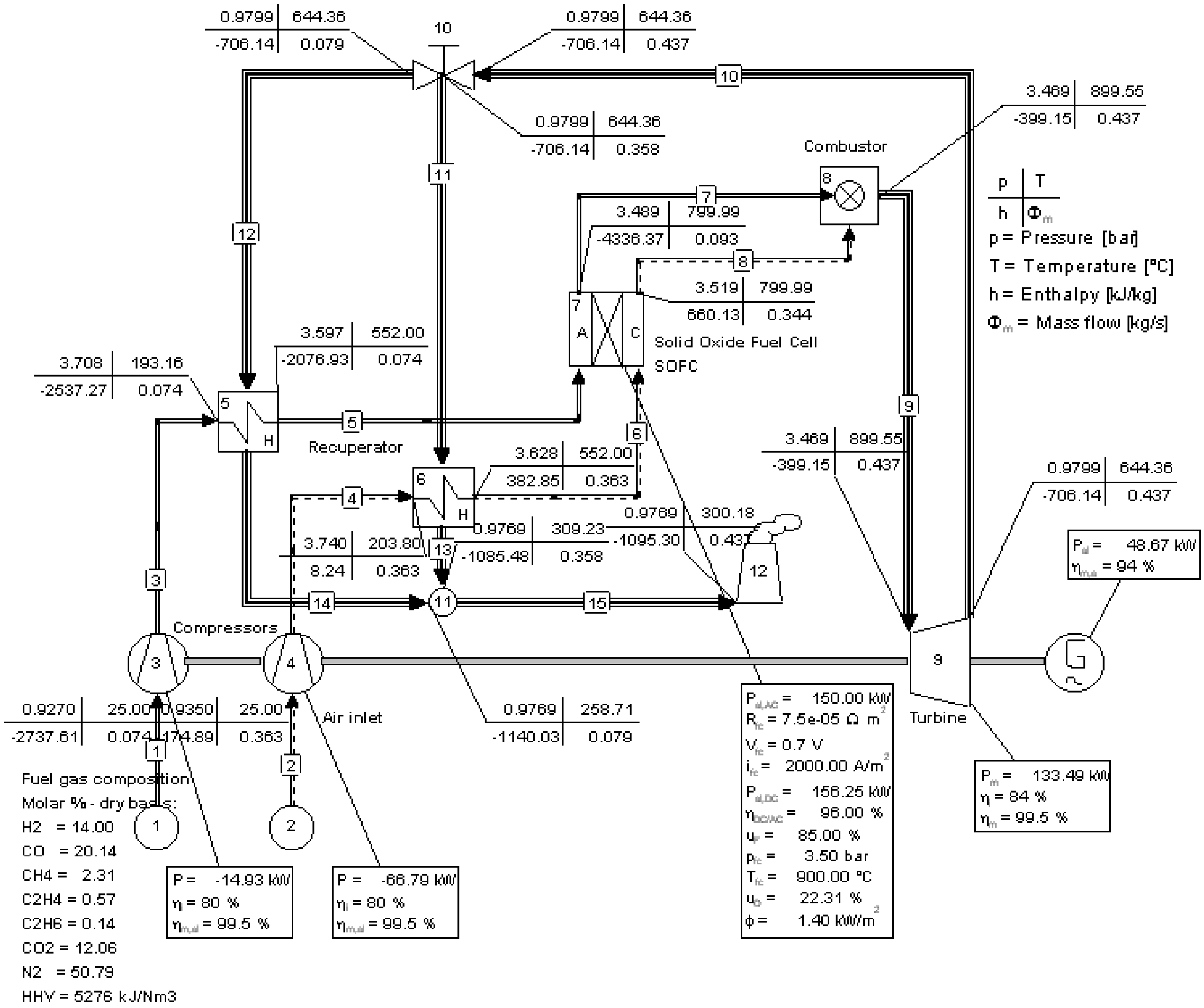

Figure 2 – Cycle-Tempo results of the biomass fuel cell/gas turbine integration

On the basis of the inlet fuel gas energy and gasifier cold gas efficiency, the inlet biomass fuel (sawdust) energy is around 538.8 kW, what does determine a need of 114.5 kg/h of residues (LHV=16,935 kJ/kg – Altafini, Wander and Barreto, 2003), e.g., 1,374.5 kg/day of 12 hours (as mentioned before).

In order to improve the gas turbine performance and of the overall system, some parameters can be varied with this purpose: (1) if the isoentropic turbine efficiency is raised to 85%, its power is increased to 50.16 kW, the overall efficiency of the subsystem fuel cell/gas turbine increases of 0.44%, and the exhaust recuperator temperature is reduced to 296.8°C; (2) if the inlet anode and cathode temperatures are increased to 560°C, the power turbine is equal to 50.03 kW, the overall subsystem fuel cell/gas turbine efficiency raises of 0.37%, and the exhaust recuperator temperature is reduced to 288.6°C; and (3) if a water steam content of 4.8% (wet basis) is considered on the dry basis fuel gas composition identified in Fig. 2, the net gas turbine power is of 49.45 kW, the overall subsystem fuel cell/gas turbine efficiency raises of 0.22%, and the exhaust recuperator temperature is reduced to 295.4°C.

From the scheme of Fig. 2, the average effectiveness of the recuperator, which is represented by two heat exchangers (components 5 and 6), was calculated to be around 80.1%, against 85% reported by Kartha, Kreutz and Williams (2000).

In the table 2, the composition (vol. %) of the SOFC anode effluents (pipe 7), along with the values refered by Massardo, McDonald and Korakianitis (2002), are presented. The high value of the CO_2 content is attributed to the water gas shift reaction, which does practically determine the difference of 0.019 kg/s between outlet (pipe 7) and inlet (pipe 5) mass flow rate of the SOFC anode. However, at the recuperator exhaust (pipe 15), the CO_2 content is of 6.85% by volume, and based on the mass flow rate of this pipe and the total electric power of the plant, a CO_2 production of nearly 0.82 kg/kWh is obtained. This value is lower than that emitted by the pulverized fuel combustion power plants (around 1.0 kg/kWh).

Table 2 – SOFC anode effluents composition (vol. %)

Specie	Present work	Massardo et al.
	%	
CH_4	0.29	-----
CO	3.87	1
H_2	1.72	1
H_2O	16.69	8
CO_2	29.65	4
N_2	47.78	74
O_2	-----	12
LHV (kJ/kg)	569.3	-----

Certainly, the composition of the SOFC effluent anode reported by Massardo, McDonald and Korakianitis (2002) presents a low value of LHV too. Thereby, the authors foresee in their scheme some natural gas supplement to the combustor. Probably, this is also the case for the plant herein analyzed.

With the aim to model the gasification and gas clean up system, one of the Cycle-Tempo models reported in Altafini, Wander and Barreto (2003) is used. This model is coupled with the fuel cell/gas turbine subsystem analyzed before. Figure 3 shows the model used, in which are identified all data involved in the analysis. The Cycle-Tempo gasifier model is simulated through two gasifier modules coupled in series. The first produces fuel gas at an equilibrium temperature of 400°C and the second at 800°C. An intermediate separation of the gas components and a subsequent separation of solid waste (2% of unconverted carbon and ashes) are considered. The gas cleaning and gas cooling sections are simulated by a moisture separator/heat exchanger and by a scrubber. The characteristics of the fuel gas produced are shown at the right side of Fig. 3, which is supplied to the fuel cell/gas turbine section.

Table 3 summarizes the main results obtained from the analysis.

Table 3 – Main results of the biomass gasification/fuel cell/gas turbine Cycle-Tempo model

Parameter	Value
Gasifier cold gas efficiency	59,4%
Sawdust mass flow rate	0.035 kg/s
Fuel gas produced to the fuel cell	0.080 kg/s
Overall energetic efficiency	38.7%
Overall exergetic efficiency	33.0%
Net fuel cell power	150 kW
Net gas turbine power	50.3 kW
Gas turbine mass flow rate	0.47 kg/s
Inlet gas turbine temperature	893.5
Outlet gas turbine temperature	639.0°C
Outlet recuperator temperature	294.7°C

4. Conclusions

Although the technologies herein treated are fairly recent, specially, those relative to the fuel cell, it is understood that this work represents a contribution to the distributed energy generation. The microturbine technology is already commercially available today, in spite of being imported. However, it seems that the systems shown can already be developed in Brazil.

Relatively to the gasification process in small reactors, its manufacturing is fairly simple, involving low investments. In the fixed bed reactors, care must be taken with the choice of the materials used in the high temperature regions, specially near the grate. The experience obtained with the gasifier used in this study allows to mention that its operation is good when the wood residue comes from planer shavings or similar. However, the operation of the gasifier with small sawdust is very difficult. Maybe, the production of pellets from this type of wood residue and its use in the fixed bed gasifier studied or other kind of gasifiers (fluidized bed or entrained flow bed) would be a good suggestion for future works. Certainly, to any type of gasifier used, optimized operation of the system will be needed to make sure high values of the cold gas efficiency (> 70%). Moreover, the gasifier and the cleanup gas system must minimizes the production of undesirable species (tar, alkalis, etc.), because probably the fuel cell operation or other kind of equipment may be highly damaged, as what happens with internal combustion engines.

Due to the relatively low value of the cold gas efficiency used in the first analysis (62.86%) or obtained in the second (59.4%), the overall energetic efficiency of the biomass gasification/fuel cell/gas turbine integration didn’t overcome 40% (36.9% and 38.7%, respectively). As said above, these low efficiencies require that there must be a special care with the operation parameters of the gasifier.

This work didn't have the intention to analyze the economic feasibility of the integrated system studied. However, it is estimated that the investment in such integration would be very high, mainly to small rural producer and agroindustrial companies. Nevertheless, considering the use of residues generated in company for the gasification, the cost of the gas produced will be lower than that of natural gas purchased from gas utilities and the gasifier efficiency isn't a key issue for the system.

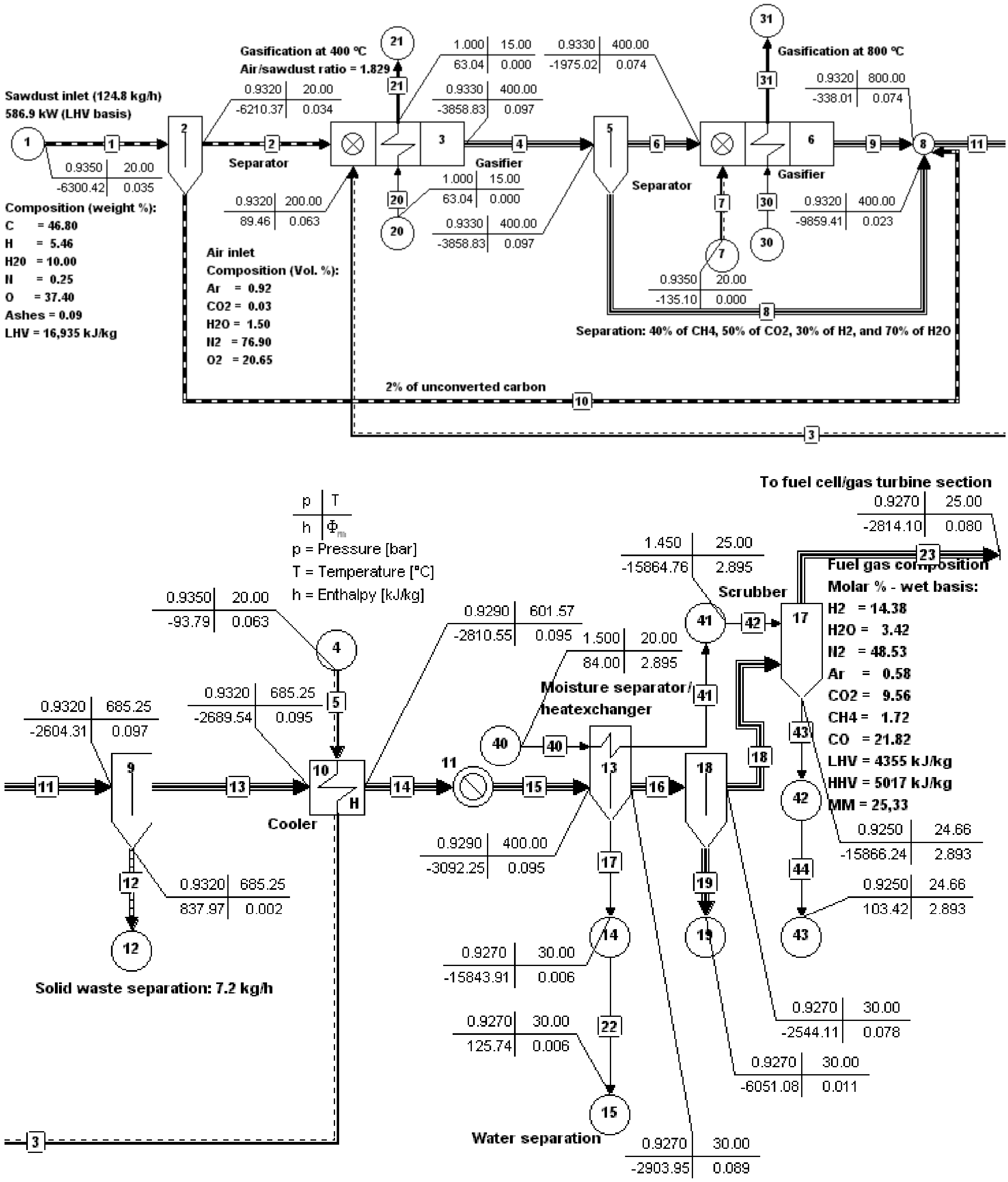

Figure 3 – Cycle-Tempo gasification subsystem with two gasifiers in series

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6. Responsibility notice

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