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Clean energy from sugarcane waste: feasibility study of an innovative application of bagasse and barbojo

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Abstract

Due to the existing difficulty of finding energy sources and reducing pollution, the use of renewable sources and highly efficient technologies for electrical energy production stands out as one of the promising solutions for the future.

This paper shows the results of the combination of these two aspects, namely, a molten carbonate fuel cell system fed with biomass derived syngas.

In particular, the biogas comes from bagasse and barbojo, the sugarcane residues. So far in developing countries they have been wasted or partly used with poorly efficient technology.

The feasibility of such an application is studied by means of the process simulator Aspen Plus© in which a detailed Fortran model has been integrated for the electrochemical reactor simulation.

The results of the predictive model are presented and discussed; in particular, the substantial economic and environmental advantages obtainable by applying the technical solution here proposed to the Peruvian energy scenario, are shown.

Keywords: Sugarcane; Biomass; Fuel cells; Plant simulation

1. Introduction

The use of biomass as an alternative energy source could play a fundamental role in reducing the use of environmentally unfriendly fossil fuels. This is true for developed countries, but even more so for developing countries where biomass is produced in large quantities but it is not fully exploited yet. Non-controlled consumption of biomass may even constitute a relevant source of environmental pollution.

The use of biomass as a renewable energy source has advantages for the development of the rural economy in terms of the application of new technologies, the creation of new jobs for biomass harvesting and manufacturing processes and the promotion of many environmental advantages.

In particular, this study has shown that Peru is a country with great potential for the production of renewable energy [1] and that the country could obtain many economic and environmental advantages from the use of biomass.

Among agricultural residues sugarcane waste, in particular, is very interesting as a renewable energy source because it is produced in abundance. However, it has not been exploited very much until now and the technology used is obsolete and, consequently, not very profitable.

Many advantages can be obtained by applying new technologies for electrical energy production to biomass.

The possibility of using these residues for energy purposes applies not only to Peru, but also to many other countries in which sugarcane cultivation is one of the most important local crops and where energy production development, linked to local economic conditions, is backward.

Typical examples are Cuba, Zimbabwe, Brazil, and India; in these countries it has been claimed that sugarcane waste can be used in the energy production system based on traditional methods.

Cuba is looking for foreign partners that want to invest in electrical power projects using biomass from sugarcane waste [2].

In Zimbabwe [3], studies have already been made on the use of bagasse energy from Zimbabwean sugar for the cogeneration of steam and electricity.

In Brazil, in addition to cogeneration studies [4], carbonisation processing of Brazilian sugarcane bagasse [5] has been carried out; in this way the pyrolisys process has been optimised producing a large quantity of charcoal that can be used for household or industrial applications.

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In India [6], models have been proposed for using sugarcane waste gasifiers and it has been suggested that the biogas produced by these reactors could be used for industrial heating applications.

Instead, in this paper we suggest that significant results can be achieved through the use of biomass with highly efficient and environmentally friendly technologies for electrical energy production such as fuel cells.

For many years the group working on electrochemical reactors at the Department of Environmental Engineering of the University of Genoa has been involved in the theoretical modelling of some families of fuel cells and it has acquired extensive experience in simulation modelling in different degrees of detail in this field [7–21].

In particular, the group, in co-operation with Ansaldo Fuel Cells, has investigated molten carbonate fuel cells, from small scale electrodes and single cells up to stacks [15–20] formed of a certain number of cells, electrically connected in series. Moreover, it has also carried out simulations of MCFC plants.

This study deals with the feasibility of an electrical power generation process using an MCFC system fed by biogas obtained from sugarcane residues.

The two parts which are possible to exploit out of the sugarcane are bagasse and barbojo.

Bagasse is the fiber of the cane obtained by milling and pressing the cane in sugar mills [22]. Bagasse is actually used marginally in the energy sector.

Normally, fossil fuels and bagasse are used to produce steam in sugar mills; the steam is partly used in the cane milling and partly in the mill's turbines to produce the electrical energy necessary for the plant [1].

However, only low energy efficiencies are obtained because of the present technologies used in the sugar mills and the boiler pollutant emissions are released into atmosphere.

Barbojo is the sugarcane trash, the tops and leaves that are abandoned in the fields after the harvesting [1].

In Peru the harvesting is normally done using traditional methods and the fields are burned to separate sugarcane trash, i.e. the barbojo, from the cane, which is not damaged in this process.

Burning barbojo generates a high level of atmospheric pollutants: partially burned carbon residues, carbon dioxide, nitrogen gases and sulphur are released; moreover the protection of the soil is hardly reduced [1].

This paper proposes the utilization of these residues as a renewable energy source, until now considered detrimental to the environment because of their difficult disposal.

To be able to use sugarcane waste as a fuel for MCFC systems it is first necessary to turn this residue into a suitable fuel gas rich in H_2, CO and CH_4 by a gasification process [22].

However, an investigation of the gasification technique to be used for sugarcane residues is not an aim of this paper and so, information and data on sugarcane gasification [23,24] and the consequent clean-up processes [25] are taken from the literature.

On the contrary, the aim of this work is an examination of the availability of the total conversion process of biogas from sugarcane into electricity, and the determination of a process solution for the MCFC plant section.

These subjects have been developed using a stationary simulation activity set-up using the commercial software Aspen Plus© [26].

In addition, in this simulation tool a detailed modelling code [16] performed in Fortran language and previously experimentally validated has been integrated to describe not only the global, but also the local behaviour of the MCFC stack.

This feature distinguishes our simulation work, usually, only simplified descriptions of the fuel cell system are considered when inserted in plant process analysis [27–30].

The MCFC section fed with the biogas refers to a power generation system planned by Ansaldo Fuel Cells, Genoa, and its usefulness for the proposed application has been verified from both energy and environmental points of view.

The plant scheme, the models and the results will be presented and discussed in the following chapters, underlining the potential effect of such as application on the Peruvian energy scenario.

2. Entire process

The entire process transforming bagasse and barbojo into electricity is schematically represented in Fig. 1.

2.1. Fuel processing

Initially bagasse and barbojo are preheated to avoid a major heat request in the gasification section, then the biomass enters an indirectly fired fluidised bed gasifier, where only steam is injected to promote biomass gasification.

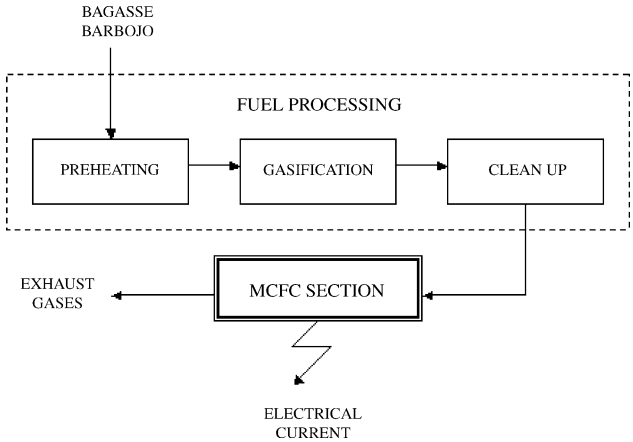

Fig. 1. The entire process from sugarcane waste to electricity.

In this way, the sugarcane residues are converted into a gas with a high low heating value (LHV) [23], containing CO, H_2, CO_2, CH_4, H_2O and small quantities of impurities such as char, tar (liquid hydrocarbons), alkali compounds and unburned carbon residues. These impurities are dangerous for the plant because they plug and foul pipes, tubes and other equipment and leads to coke deposition on the fuel reforming catalyst or on the fuel cell electrodes [24], so a suitable clean-up procedure is necessary.

An example of a clean-up procedure is suggested by CIRPS [24], which considers cyclones as the first clean-up procedure to remove a portion of the char, the particulate matter and the tar from the gaseous stream.

Then the remaining tars are cracked into smaller molecules in a tar cracker on the catalyst surface.

The gas passing through the reactor is cooled by the heat exchanger located in the tar cracker, so the alkali and tars not cracked condense on the catalyst surface and can be removed from the gaseous stream [24].

This hot gas conditioning permits tar disposal by cracking it to gases useful to feed MCFCs.

Finally, the gas is purified in bags filters before entering the MCFC section [24].

2.2. MCFC section

This section is the specific object of the process analysis presented in this work.

The MCFC system considered here for the study of the transforming process of biogas from bagasse and barbojo into electricity belongs to Ansaldo Fuel Cells [31,32].

In the following both the MCFC system scheme so as represented by means of the simulation software (Fig. 2) and the main simulation assumptions will be presented.

The plant is fed by biogas coming from Peruvian bagasse and barbojo gasification; the fuel enters the Reformer after it has been warmed in a cross-flux heat exchanger Reghex using hot gases coming from the same reformer.

Fuel preheating is necessary because of the endothermic reforming reaction:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

which is favoured by high temperatures, and, when is under way, occludes heat and tends to lower the reactor temperature. In the model the reaction has been assumed at thermodynamic equilibrium.

Through the reforming reaction CH_4, which is present in the feeding stream, is transformed into CO and H_2, useful gases to feed MCFC stack.

Moreover the shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

also takes place in the reformer, giving H_2 and CO_2 and so enriching the biogas further. This reaction also has been considered at thermodynamic equilibrium in the model.

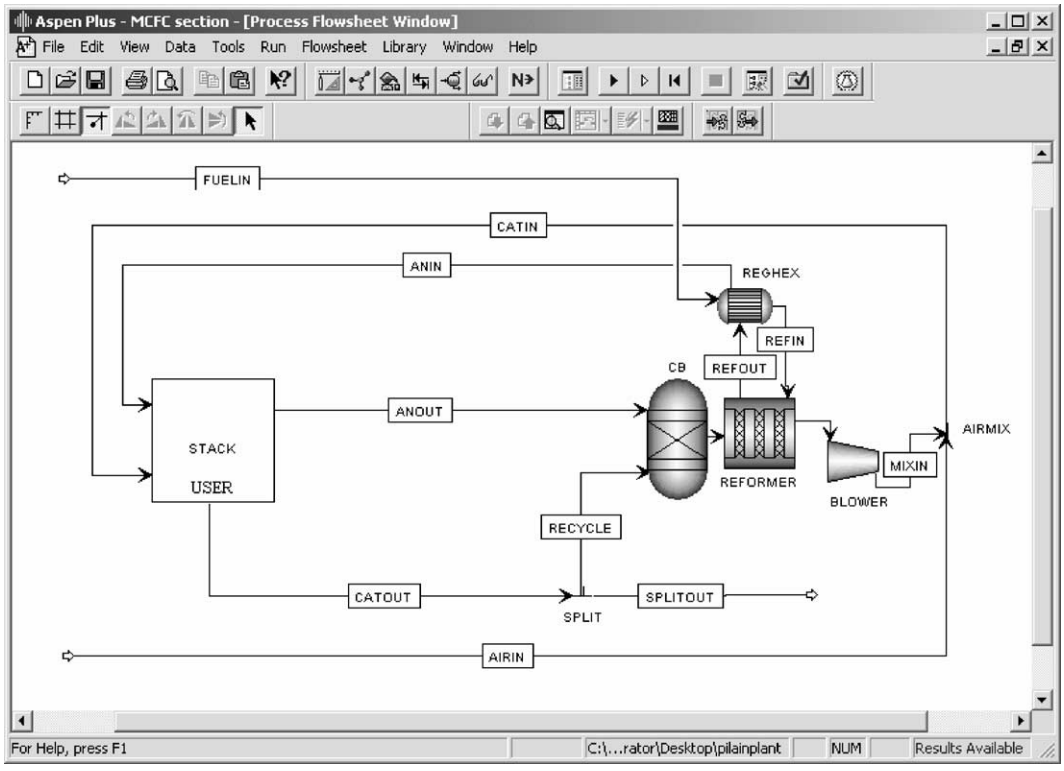

Fig. 2. MCFC section.

Reformed fuel comes out from the reformer hot and exchanges heat with the feeding stream in the heat exchanger; then it enters the anodic side of the stack.

In particular, as the stack inlet stream temperature is an important key for a proper MCFC operation (see Section 4), the heat exchanger properties have been set in such a way to guarantee a suitable anodic inlet temperature of 600 °C.

Instead, the cathodic side is fed with air that, before entering the electrode, is mixed with the cathodic exhaust gas in the mix Airmix.

The MCFC stack produces a direct electrical current by means of the electrochemical processes that take place inside it.

The MCFC stack model will be described in detail in the next chapter.

The gaseous stream that is present at the anodic exit contains unreacted H_2, H_2O and CO_2 coming from the electrochemical reaction in the anodic zone, little quantities of unreacted CO and CH_4, and N_2.

Instead, at the cathodic exit a gaseous stream containing unreacted O_2, CO_2, H_2O and N_2 is obtained.

This gaseous stream is partly (about 40%) released into the atmosphere (Splitout), and partly channelled into the burner CB (Recycle) in which it is mixed with the anodic gaseous stream.

The stack exhausts mixed in this way react through the following oxidation reactions:

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

which, in the model, involve the total combustion of the unreacted anodic gases thanks to the cathodic O_2.

These reactions are exothermic and so they generate heat, therefore, steam and CO_2 created in the burner enter the reformer with the unreacted stack gases; here they exchange heat with the feeding stream and so the necessary heat for the reforming reaction is produced.

The gases leaving the reformer regain pressure in a blower and then they are mixed with the air that is fed to the cathodic size.

The section scheme described above has been simulated using the Aspen Plus© software that allows the use of prebuilt-up models reproducing the principal elements of a chemical system.

In this case standard models have been applied to certain system elements, such as the heat exchanger, the reformer, the split, the airmix, the burner and the blower.

A software Aspen Plus© interface allows the creation of personalized models in Fortran language. In this way it is possible to create non-standardized models. In particular, an original specific Fortran model has been integrated here to simulate the electrochemical reactor, as discussed in the following chapter.

2.2.1. Electrochemical reactor

The electrochemical core of the plant consists of a fuel cell stack that directly converts chemical energy into electricity.

Many types of fuel cells are being studied at the moment. Of these, MCFCs have been chosen. These are interesting because of their high operating temperature (∼650 °C), which allows the use of non-noble catalysts, cheap and insensitive to some fuel contaminants which poison other cells; MCFCs therefore can be fed by fuel containing CO_2, such as biofuel [15].

MCFCs are usually planar cells formed by a matrix (tile) filled with Li and K carbonates and coupled with two electrodes where the following electrochemical reactions occur:

$$\text{anode}: \quad {CO_3}^{2-} + H_2 \rightarrow CO_2 + H_2O + 2e^- \tag{1}$$

$$\text{cathode}: \quad CO_2 + \tfrac{1}{2}O_2 + 2e^- \rightarrow {CO_3}^{2-} \tag{2}$$

$$\text{overall reaction}: \quad H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

The fuel and the oxidant are fed separately, and the tile prevents gas crossover and guarantees an adequate ionic conduction and electronic insulation [16].

The stack is composed of a number of superimposed cells connected in series, via bipolar plates to supply the requested power.

In this work the MCFC stack has been simulated by means of a code programmed in Fortran language and integrated in the plant simulation, so that the input data for the model are in part directly supplied by the user (i.e. the electrochemical kinetics parameter and the operating current density) and in part imported from the plant loop results calculated by Aspen (i.e. the physical properties of the gaseous streams at the stack inlet).

This electrochemical model has been set up by the authors and validated using experimental data coming from Ansaldo MCFC system technology [16–20].

It is three-dimensional one, but in this case the cells of the stack are considered as a package of consecutive cells and for each one the same working conditions are calculated.

On the cell plane the maps of the main chemico-physical properties are calculated on the basis of mass, energy and momentum balances as well as on a detailed electrochemical kinetics.

Among the calculated variables are the solid temperature, the anodic gas and the cathodic one, the current density and the resistance; the open-circuit voltage, the gas composition and the gas flow; the pressure drop on the cathodic side and on the anodic one.

Analysing these maps it is possible to check the performance of the principal variables of the process, to identify possible critical situations and to choose better operating conditions.

Table 1
Composition (mol%) and LHV (MJ/Nm^3) of gas coming from gasifier

Gas coming from gasifier (mol%)	
CH_4	4
CO	22
CO_2	16
H_2	46
H_2O	12
LHV[a]	8.7

[a] In MJ/Nm^3.

3. Simulation activity

This paper now presents a theoretical analysis of the application of biogas coming from sugarcane waste gasification with a specific electric power generation planning solution.

For this purpose, the MCFC section (see Section 2.2) running is checked by the Aspen Plus© simulation in which the electrochemical model [16] has been integrated.

In the following chapters the data and operating conditions for the simulation are analysed, the simulation results obtained are discussed and the relative conclusions drawn.

3.1. Data and operating constrains

The MCFC section has been fed with biogas obtained from indirectly heated gasification of bagasse and barbojo using a fluidised bed gasifier [24].

The composition (mol%) and LHV (MJ/Nm^3) of the gas coming from the gasifier are given in Table 1 and the main MCFC stack operating conditions are summarized in Table 2.

The simulated stack supplies about 250 kW, and it is composed of 300 molten carbonate fuel cells.

To discover the right feeding flow to the MCFC section, a maximum 75% fuel utilization in the MCFC stack is imposed; in fact, higher utilization factors involve a performance decay due to their behaviour in diffusion limiting conditions [18].

Some devices have to be applied before feeding the electrochemical section so dangerous situations for plant safety running are avoided.

In particular the water content of the gas must be modified to preclude the Bouduard reaction:

$$2CO \rightarrow C + CO_2$$

in which the CO fed to the plant changes into CO_2 and C: carbon deposition is dangerous for the system because it obstructs the gas passage and reduces stack efficiency.

Adding water to the feeding precludes the Bouduard reaction because the shift reaction is promoted:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The overall reaction is the following:

$$C + H_2O \rightarrow CO + H_2$$

The calculation of the right water flow has been made using the Aspen module “Gibbs reactor” [26].

In this way the water content necessary to avoid carbon in the plant piping has been calculated: the right fuel flow for feeding the MCFC section is 34.6 kmol/h.

So, the composition (mol%) and LHV (MJ/Nm^3) of the gas fed to the electrochemical section are given in Table 3.

It has been assumed that the feeding flow temperature of the fuel is equal to 450 °C and the air equal to 137 °C on the basis of the behaviour of the upstream components, the clean-up [24] and the air compression systems, respectively.

The operating pressure has been set up at about 3.6×10^5 Pa because of the optimal performance of the MCFC system at this pressure.

Finally, an operating current density was chosen in order to define the MCFC plant section running conditions; in particular, to guarantee a proper cell voltage of about 0.7 V, the assumption of 1674 A/m^2 has been formulated.

3.2. Discussion of results

Fixed the above main data and taking account of operating conditions, the fresh air feeding to the cathodic side was to be defined.

This parameter strongly affects the thermal management of the plant, and in particular the operating temperature of the MCFC stack, also because the anodic inlet temperature has been already fixed at 600 °C (see Section 2.2).

Table 2
MCFC stack operating conditions

Operating conditions	
Cells number	300
Cell area (m^2)	0.711
Supplied power (kW)	250
Current density (A/m^2)	1674
Fuel utilization (%)	75
Feeding flow (kmol/h)	10.6
Feeding temperature (K)	723
Operating pressure (Pa)	3.6×10^3

Table 3
Composition (mol%) and LHV (MJ/Nm^3) of gas fed to electrochemical section

Gas fed to MCFC section (mol%)	
CH_4	1.2
CO	6.7
CO_2	4.9
H_2	14
H_2O	73.2
LHV[a]	2.6

[a] In MJ/Nm^3.

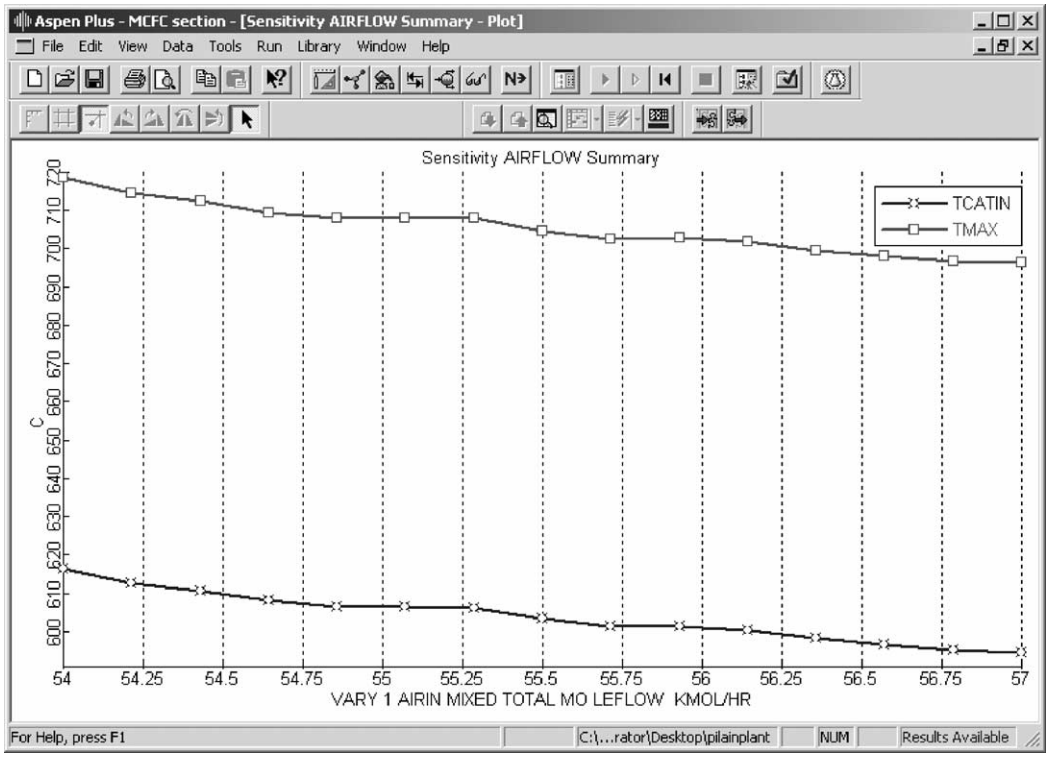

Fig. 3. Parametric analysis of the cathode inlet temperature (°C) and the maximum stack temperature (°C) vs. the MCFC section inlet air flow (kmol/h).

So the air flow rate has been chosen considering that stack inlet stream temperatures of at least 580 °C are necessary to guarantee a good ionic conduction inside the stack, while stack temperatures higher than 700 °C is to be avoid because they can cause problems such as electrolyte loss and corrosion for the MCFC.

Fig. 3 presents the parametric analysis of the cathode inlet temperature and the maximum stack temperature versus the MCFC section inlet air flow.

From an analysis of this plot it appears that 56.5 kmol/h of air permits a cathode inlet temperature of 600 °C; at the same time, the temperature in the stack does not exceed 700 °C, as also shown in the solid temperature map (Fig. 4), observing the safety limit that guarantees the correct running of the MCFC section.

Moreover, this air flow does not generate an excessive pressure drop along the electrodes during the simulation, so problems linked to gas escape between the electrodes are avoided; in fact, analysing the pressure drop anode/cathode map (Fig. 5), it appears that the maximum pressure drop attained in the stack is 1.68×10^3 Pa, inferior to the maximum recommended value of 2×10^3 Pa [17].

Therefore, the optimum work conditions for a correct running of an MCFC stack have been determined with the Aspen simulation.

The most relevant results which characterise the identified working condition are summarized in Table 4.

The integration of the simulation electrochemical model and the Aspen code has been demonstrated to be very important for checking local limits of the parameter; moreover, it has made it possible to make a rough estimate of the running of the MCFC section.

Table 4
The most important simulation conditions

Oxidant flow (kmol/h)	56.5
Anode inlet temperature (°C)	600
Cathode inlet temperature (°C)	600
Anode outlet temperature (°C)	645
Cathode outlet temperature (°C)	688
Current density (A/m^2)	1674
Medium pressure drop anodic size (Pa)	-6×10^2
Medium pressure drop cathodic size (Pa)	-16×10^2

In addition, it should be noted that a previous process analysis performed using the same Aspen models, but with a simplified MCFC simulation model which did not take local balances into account resulted in the calculation of a different optimal air flow, that is about 68 kmol/h.

The simplified different results appear to be affected by two risky approximations when compared to calculations performed with the detailed code: the simplified model calculates stack inlet conditions that, if really achieved, involve a local temperature on the cells higher than 700 °C, while at the same time it overvalues the feeding air flow so that plant temperatures could be lowered excessively (also down to 580 °C if more detailed calculations are performed). So, results that do not appear to be very

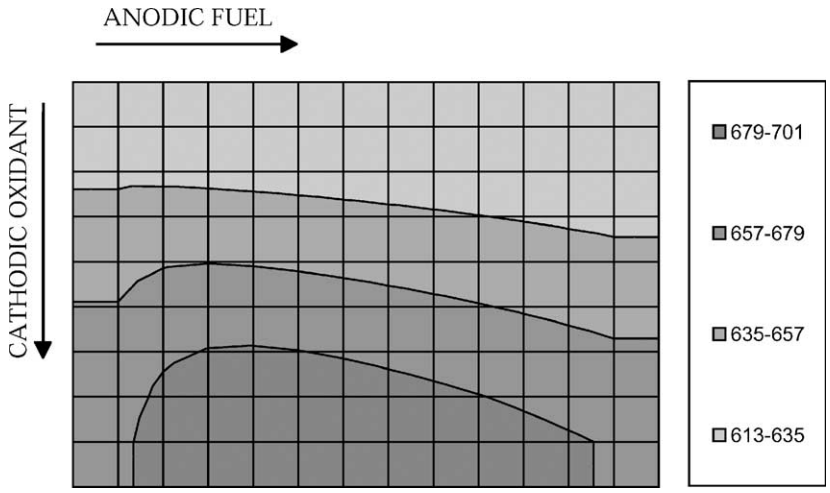

Fig. 4. MCFC solid temperature (°C) map.

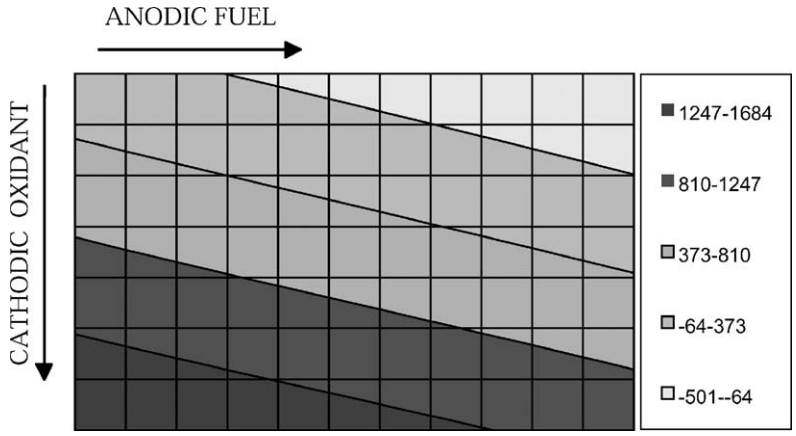

Fig. 5. Pressure drop anode/cathode (Pa) map.

different, really can involve critical operating conditions for the stack.

The importance of the incorporation of a detailed code in the plant simulation has been demonstrated also by another parametric study performed. In Fig. 6 the maximum temperature in the stack and the minimum one versus current density are shown.

The current density has been reduced from the reference value to 1500 A/m^2 in order to verify the choice for the operating electrical charge. Higher current densities have not been considered, because, for the same value of fuel fed, they involve fuel utilization factors higher than the maximum limit of 75%.

The results in Fig. 6 show that temperatures slightly decrease in the stack as current density increases, even if they usually increase dramatically as current density increases if MCFC behaviour is considered isolated and not integrated in the plant.

In fact, greater fuel utilization factors involve higher heat production in the stack because of exothermic electrochemical reactions, but globally this feature is balanced by a lower heat production in the burner, where a lower quantity of unreacted gas is oxidised.

However, this does not provide a constant plant temperature because of the conversion of fuel chemical energy into electric energy in the MCFC system and not into thermal energy in the combustion process (so the temperature decreases when the fuel is electrochemically converted rather than burned).

Nevertheless, this effect is not very significant in the analysed range and so thermal management is practically invariable from current density.

In the light of these considerations and calculating that electric power linearly increasing from 235 kW at 1500 A/m^2 up to 255 kW at 1674 A/m^2, the choice of a working condition of 1674 A/m^2 has been confirmed.

Finally, it appears that the quantity of converted methane is small and 68 kW still exits from the heat exchanger; therefore, a modification can be made to the Ansaldo scheme plant for the specific application of this paper: the elimina-

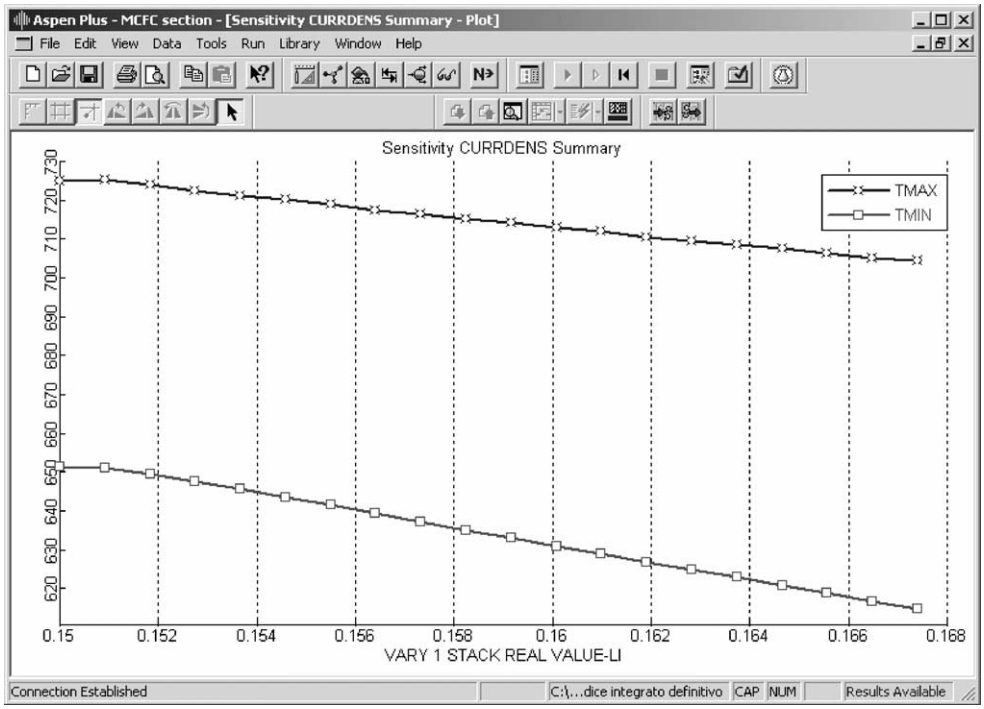

Fig. 6. Parametric analysis of the maximum temperature (°C) in the stack and the minimum one (°C) vs. current density (A/cm^2).

tion of the reformer (for example, pushing gasification further toward H_2 production) and the combining of the burner and the gasification section.

However, the results show the feasibility of generating electric power using an MCFC power plant fed by biogas from bagasse and barbojo.

4. Application to Peruvian energy scenario

On the basis of the results discussed in the previous chapter, the quantification of the total energy that can be obtained using the overall sugarcane residues produced in Peru is now presented.

In particular the annual electric power generation is evaluated here for the year 2000, knowing that in this reference year the Peruvian production of bagasse and barbojo, useful for energy purposed, was about 3.36×10^9 kg [22,33].

If about 160 Nm^3/s of biogas can be obtained from such a quantity of sugarcane waste by gasification (1.5 Nm^3/kg of biomass according to [24]) and if a 255 kW module is fed by 0.06 Nm^3/s (as determined by our calculations above), about 2376 modules of 255 kW can be fed and so 2.18 Tera Watt Hours of electricity can be produced.

Even if a rough estimate of the energy consumption necessary during the gasification and clean-up phases is considered—these system sections indeed are going to be studied in detail in the future—the electric power generation process proposed in this paper is more profitable in terms of produced power, than the present Peruvian electrical energy production process using bagasse and traditional technology in sugar mills.

In fact, in the same year 2000, 0.05 Tera Watt Hours was generated in Peruvian sugar mills by using part of the bagasse together with fossil fuel in a turbine.

Further benefits of this innovative solution are represented by the environmental advantages due to the elimination of the traditional open burning of sugarcane and the reduction of the pollutants emitted by sugar mill boilers.

The use of sugarcane waste of Peru for fuelling MCFCs may seem quite considerably expensive option; however, the total energy potential concerned in the proposed project may suggest to consider the plant start-up, even on a small scale, paying attention to the conditions in developing countries.

In conclusion, this paper underlines how the project of exploiting bagasse and barbojo in Peru by using highly efficient technologies for the production of electrical energy, such as fuel cells, presents a higher energy output than the present power plant generation technology.

Moreover, considering the actual environmental problems linked to sugarcane waste disposal, the project proposed in this paper offers the prospect of clean energy in which sugarcane residues from unused waste are converted into a renewable energy source.

5. Conclusions

This paper proposes the use of the sugarcane residues bagasse and barbojo and highly efficient and environ-

mentally friendly fuel cells for the production of electric energy.

In particular, it has been pointed out that Peru produces large quantities of sugarcane waste but barely uses them for energy purposes, instead using obsolete and unprofitable technologies.

Moreover, the emissions produced by sugar mill boilers and the open burning of barbojo generate high atmospheric pollution.

This paper proposes a process solution in which bagasse and barbojo are converted into clean biogas with a high low heating value, suitable for feeding an MCFC section simulated with the commercial software Aspen Plus© integrated with a detailed electrochemical model that is able to simulate an MCFC stack.

The importance of the integration of this model and the Aspen plant for checking local limits of the parameter has been demonstrated. Moreover, it has permitted the determination of a rough approximation of the running of the MCFC section, showing that the simulation results obtained are more substantial than the ones obtained from a plant simulation where a simplified MCFC stack model was used.

It has been demonstrated that Peru could obtain many advantages by applying this process solution to bagasse and barbojo; the overall net electricity production obtainable using in innovative way all the sugarcane residues produced in Peru is estimated significantly greater than the actual power generated by sugar mill boilers using bagasse and fossil fuel.

At the same time, boiler emissions could be reduced and the atmospheric emission from barbojo burning could be eliminated.

So, it appears that these qualitative and quantitative energy improvements can be an interesting prospective for Peru and for all countries which want to invest in sugarcane.

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