

BIOMASS GASIFICATION AND FUEL CELL INTEGRATION: THE POTENTIAL AND EFFICIENCY

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Abstract: This work presents an energy analysis of generation systems based BIGFC Biomass Integrated Gasification Fuel Cell. Was simulated the use of synthesis gas from cane bagasse gasification at two fuel cells, the PEMFC and SOFC. The PEMFC can only operate with pure hydrogen fuel, and, therefore the synthesis gas must pass for a processing that understands mainly in the conversion of the carbon monoxide (CO) or shift reaction, and the shift gas cleaning in PSA Pressure Swing Absorption. The SOFC can operate with synthesis gas fuel directly due high operating temperature. The results had demonstrated that PEMFC has a low potential to generate energy from the biomass gasification, therefore the separation of hydrogen of the gaseous flow result in many energy losses. The other hand the SOFC has great potential for integration with biomass gasification, presenting a good electric efficiency and also potential for co-generation.

Key words: Fuel Cell, hydrogen, gasification, biomass, integration.

1. Introduction

The Fuel cell (FC) converts a fuel, generally the hydrogen, directly in electricity and heat through electrochemical reactions. The hydrogen can be produced from some sources such as the water, ethanol, natural gas and biomass. The respective processes for attainment of this gas are the electrolysis of water, the ethanol and the natural gas reform and the biomass gasification.

The biomass gasification produces a synthesis gas generally composed for hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2) and nitrogen (N_2). The relative amounts of these gaseous species in accordance with the type of reactors, the biomass type, gasification agent (air, oxygen, steam) and the operating temperature. The synthesis gas also contains impurities. These understand the particles, tar, alcalis (Na and K), ammonia (NH_3) and sulfur species (H_2S).

Aiming at the use of this synthesis gas in fuel cells (FC) is necessary there are a cleaning system for removal of impurities and a processing system. This consists of the removal of the inert gases as nitrogen (N_2) and the carbon dioxide (CO_2), and the conversion of the carbon monoxide (CO shift) and methane (CH_4 reforming) for hydrogen (H_2) production. For electricity generation in a low-temperature FC ($80^\circ C$), as PEMFC (Proton Exchange Membrane Fuel Cell) it has necessity of an extensive gas processing the until it only has hydrogen in the gaseous flow. On the other hand the use of the synthesis for electricity generation in a high temperature FC ($1000^\circ C$), as SOFC (Solide Oxide Fuel Cell) needs a less complex gas processing, a time that the SOFC has the option of internal reforming of methane to generate hydrogen and the carbon monoxide can be used as combustible. The greater or minor complexity of the synthesis gas processing, respectively will result in a greater or minor energy losses of the system. The objective of this paper is to present the necessities for processing of synthesis gas generated from the gasification of sugar cane bagasse in a system with PEMFC and a system with SOFC, as well as the balance sheet of energy in each case.

1.1 Technology of the biomass gasification

The processes of simpler gasification use air, the synthesis gas produced presents itself sufficiently diluted to nitrogen of air and a lower heating value of 5.000 kJ/Nm^3 . When using itself pure oxygen increases the lower heating value of the gas stops up to 10.000 kJ/Nm^3 at the same time where if it diminishes the scale of the gasifier and other equipment; the disadvantage is the additional cost of a technology for oxygen separation. Also it has processes of gasification with indirect heating, in these is made a high temperature (900°C) biomass pyrolysis and the produced coal is circulated for a combustor that produces the necessary energy for the pyrolysis. The gas produced in these systems is practically free of nitrogen Bain (2004).

The composition of the synthesis gas is important, which had the differentiation in the characterization and sizing of the processing system for one determined type of fuel cell.

1.2 Integration of the biomass gasification and fuel cells

Some theoretical studies had been carried through on the integrated biomass gasification fuel cells, these systems are called by BIGFC (Biomass Integrated Gasification Fuel Cell). The subject little was explored, still has few experimental data, but some projects for construction of pilot plants exist in the world.

The combination of the FC technology with the gasification systems is not a new idea; this can be considered as an effort to improvement the level of the efficiency of systems conversion based on the coal gasification. These systems are mentioned as IGFC Integrated Gasification Fuel Cell.

In August of 2003, in U.S.A., a IGFC pilot plant for demonstration ends was inaugurated. This pilot plant localizes in a great plant of coal gasification, to use a small part of the synthesis gas in a FC type MCFC (Molten Carbonate Fuel Cell) model DFC3000 with 1 MW power electric (FUEL CELL ENERGY, 2003).

To generate electricity, using the synthesis gas produced from the coal, in FC is form of a more efficient and cleaner exploitation of this resource. However, the coal is a not renewable source and its exploitation for electricity generation is not sustainable in long time. Beyond that the withdrawal of this resource of the terrestrial crust present serious environmental problems. The biomass on the other hand is a renewable source, and the involved ambient problems in the exploration of this source for electricity generation well less when are compared with the coal.

The first efforts of research for the integration of FC and biomass gasification for electricity generation had appeared in the years 1970 due one mainly the petroleum crisis. But it has been recently that the research in this area has gained more attention.

Between the theoretical studies that had been developed are cited, for example, Lobachyov & Richter (1998), McIlveen-Wright et. al. (2000). These had analyzed the theoretical efficiency of FC type PAFC (Phosphoric Acid Fuel Cell) and MCFC (Molten Carbonate Fuel Cell) operating with the synthesis gas from the wood gasification. The electric efficiencies estimates for PAFC and MCFC, considering the lower heating value of the wood, had respectively been of 16,6% and 29%.

Kivisaari et. al. (2002) had investigated the influence of the internal reforming of the methane, contained in the synthesis gas, in the electric efficiency of generation in FC type MCFC in cycle combined with steam turbine. An air fluidized bed gasifier was considered, for wood, the synthesis gas with a composition of 4,5% CH_4 , 14% H_2 , 19% CO , 11% CO_2 , 39% N_2 . For a gasification temperature of 900°C and pressure of 500 kPa the electric efficiency of the system increases respectively of 36% for 43% without internal reforming and with internal reforming.

In the Energy Research Center in Holland, in the Fuel Cell and Biomass Department, Oudhuis et. al. (2004) had carried through tests with a FC type SOFC operating with the synthesis gas of biomass. An 1 kW fuel cell was integrated to small gasifier for residues of the paper mill industry. The experimental electric efficiency of the SOFC was of 41% with relation to the lower heating value of the synthesis gas.

1.3 Fuel Cells (FC) type PEMFC and SOFC

The FC type PEMFC already is commercial a half technology. It is adjusted applications to vehicles and for distributed generation. The main components of this fuel cell are: the polymer membrane of protons exchange (hydrogen ion); a diffusing porous layer; a catalyst layer (in the electrodes) situated between the porous layer and the membrane; and the bipolar plate with flow canals for the gas fuel (anodo) and the gas oxidant (cathode) distribution for the reactive parts of fuel cell (FERNG, et al., 2004). Generally this type of FC operates with temperatures below of 100°C (in the band of 60 80°C) the atmospheric pressure, because the polymer membrane available currently depend on water to develop an acceptable ionic conductivity.

The FC type SOFC still meets in research and development. But it is considered most promising for generation distributed with co-generation due to high operating temperature (in the band of 800 1000°C) what it makes possible the internal reforming of hydro-carbons as the methane and the possibility to use the carbon monoxide as combustible (ENERGY CENTER, 2000).

Prototypes of SOFC in functioning exist. They are in phase of tests for companies as the Siemens-Westinghouse, General Electric and Rolls Royce. In the year of 1999, Siemens-Westinghouse placed in functioning, for test ends, a 250 kW power module consuming natural gas fuel. The SOFC generates 200 kW of electric power to a pressure of 350

kPa and a gas turbine generates 50 kW of electric power using the fuel cell exhaustion gases. Its income is placed enters 55% and established 60% in the lower heating value of the natural gas (SINGHAL, 1999).

2. Methodology

2.1 Gasification system considered in the study

For this study a circulating fluidized bed gasification system was considered. The biomass, palletized sugar cane bagasse, enters in the gasifier with a mass outflow of 500 kg/h. The operating temperature of the gasifier is 850°C, the synthesis gas passes through two cyclones that remove most of the particles material. After that the gas enters in a reactor, also of circulating fluidized bed, for tar removal. After this reactor the gas is cooled of 850° C for 240°C, and passes for a cyclone, one bag filter, and finally wet passes for one wet scrubber where it is cooled until 30°C (ambient temperature) for condensation of the remaining tar. The figure below illustrates this gasification system.

The gasification of the sugar cane bagasse in this in case that it is carried through with air, in way that the synthesis gas sufficiently is diluted with nitrogen. The composition of the synthesis gas is 10% H₂, 56,4% N₂, 12,7% CO, 3,7% CH₄, 16,7% CO₂, and 0,5% C₂H₄ in dry base, to the ebb tide of wet to scrubber. The lower heating value of this gas is of 3.900 kJ/Nm³.

2,2 Gasification system integrated with FC type PEMFC

The gaseous flow for feeding of the PEMFC must be pure hydrogen, exempts mainly of carbon monoxide. The PEMFC is sensible to the presence of this gas, the maximum CO concentration tolerated is 10 ppm. For in such a way the system of processing of the synthesis gas he is described as it is illustrated in figure 1. The synthesis gas after to leave wet scrubber to a temperature of 30°C is reheated until 500°C and mixed with steam water, for CO shift conversion. This chemical reaction of shift is catalytic and exothermic, and results in the production of hydrogen H₂ and carbon dioxide CO₂, according to Eq.(1):



They are two shift reactors, the high temperature one, 500°C and the low temperature one, 250°C. The first shift reactor is cooled with air so that shifted gas has left 250°C. After these reactors the shifted gas must pass for a condenser to be cooled until 55°C, losing the humidity, so that it can pass through PSA purification.

The PSA Pressure Swing Adsorption, sufficiently is used for purification of hydrogen generated from the natural gas reforming, an example is the reforming reactor of natural gas developed by the Hydrogen Laboratory of the UNICAMP. The PSA, basically, functions for the action of a selective adsorbent bed stream the determined gaseous species. A gaseous mixture is introduced in the stream bed to a high pressure (800kPa – 1000 kPa) and the solids adsorbents "adsorbs" selectively determined gaseous components, allowing that to the component not adsorbed pass through the stream bed as purified gas product.

In the specific case of this paper the synthesis gas is compressed until a pressure of 1000 kPa, and this gases CO₂, N₂, CH₄ and C₂H₄ selectively are adsorbed. While that only the hydrogen H₂ passes through the system. After one determined time the stream bed of the PSA arrives the saturation condition. To regenerate it is necessary the depressurization of the purification column. The gases are rejected, being that CH₄ and C₂H₄ are combustible and can be used for steam generation for shift reaction.

The purified hydrogen arrives in the fuel cell where electrochemically it is converted into electricity. The FC does not convert hydrogen total, has a fuel utilization factor U_f, which must be considered. The value of the U_f generally is of 80%, as reported for DOE (2002) and Larminie & Dicks (2003).

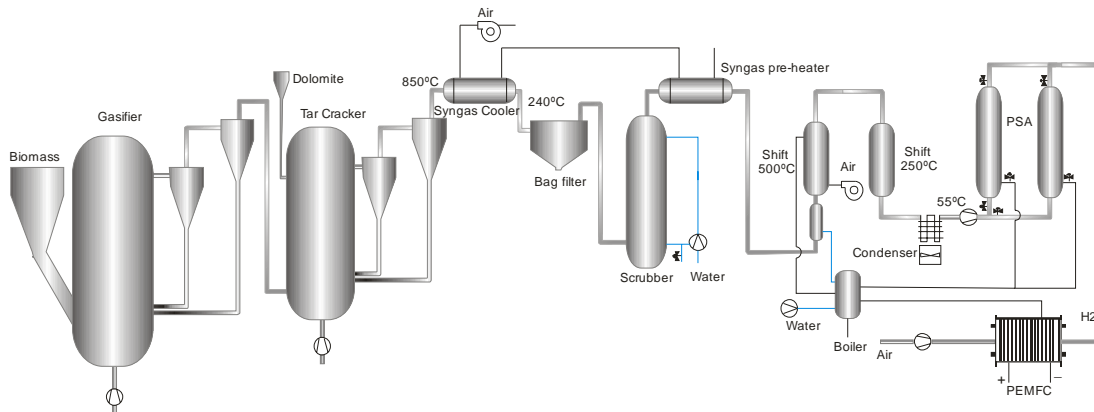


Figure 1 schematically Diagram of the PEMFC system

The used methodology was the energy balance in permanent regimen for each control volume of the system equipments, not considering the variations of kinetic and potential energy, according to Eq. (2) and Eq. (3):

$$\dot{Q}_{vc} + \dot{W}_{vc} + \sum \dot{m}_e h_e - \sum \dot{m}_s h_s = 0 \quad (2)$$

Where:

\dot{Q}_{vc} = heat transfer (kJ/s);

\dot{W}_{vc} = work (kJ/s);

\dot{m} = mass outflow of the work fluid (kg/s);

h = specific enthalpy (kJ/kg)

$$\dot{Q}_{vc} + \dot{W}_{vc} + \sum \dot{N}_i h_e - \sum \dot{N}_i h_s = 0 \quad (3)$$

For the chemical reactions of reforming, shift and calculation of flame temperatures, the Eq.(4):

$$H_{RP} = \sum_i (N_i \bar{h}_i)_P - \sum_i (N_i \bar{h}_i)_R \quad (4)$$

Where:

H_{RP} = difference of the enthalpies of the reagents and the products (kW);

N_i = molar Flow of species i (kmol/s);

h_i = molar specific enthalpy of species i (kJ/kmol).

The electric power produced by a fuel cell is defined by the Eq. (5):

$$W_{el} = \left[\sum_i (N_i \bar{h}_i)_R - \sum_i (N_i \bar{h}_i)_P \right] - T \left[\sum_i (N_i \bar{s}_i)_R - \sum_i (N_i \bar{s}_i)_P \right] \quad (5)$$

Where:

W_{el} = produced electric power (kW);

T = absolute temperature (K);

s_i = molar specific entropy of species i (kJ/kmolK)

The electric efficiency of the fuel cell is defined by Eq.(6):

$$\eta = \frac{W_{el}}{\dot{m}_c LHV} \quad (6)$$

Where:

\dot{m}_c = mass fuel outflow (kg/s)

LHV = lower heating value of fuel (kJ/kg).

The electric efficiency can be defined with relation to the hydrogen energy content, in the case of the PEMFC, and in this paper 50% were considered equal.

The electric efficiency of the system generation is calculated in relation to the lower heating values of the synthesis gas and of the sugar cane bagasse.

2.3 Gasification system integrated with FC type SOFC

The use of biomass synthesis gas FC type SOFC is described as it is illustrated in figure 2, the methodology of the energy balance is same that the used one for the case of the PEMFC.

The PSA was located to the sum of the gasifier for separation of the oxygen and nitrogen from air. Of this form the gasification is carried through with pure oxygen modifying the composition of the synthesis gas described previously. The synthesis gas is cooled of 850°C for 200°C. But in this system the heated air that leaves cooler is directed for a pre-heater in order to increase the temperature of 450°C to be used in the cathode of the fuel cell.

In this system it does not have necessity of shift reactors, a time that the SOFC can use the carbon monoxide directly as combustible. The anode of the SOFC is fed with a gaseous mixture contends H_2 , CO , CH_4 , C_2H_4 and CO_2 , due to this the SOFC will not have the maximum efficiency that it would have in the case of the operation with pure hydrogen. The

methane internally reacts with steam in the SOFC, is the reforming reaction that produces hydrogen and carbon monoxide, according to Eq.(7). The water requirement for the internal reforming of methane, in this paper was calculated on the basis of the relation steam: carbon equal 1:1. This relation can be of 3:1 as reported Leal (2003).

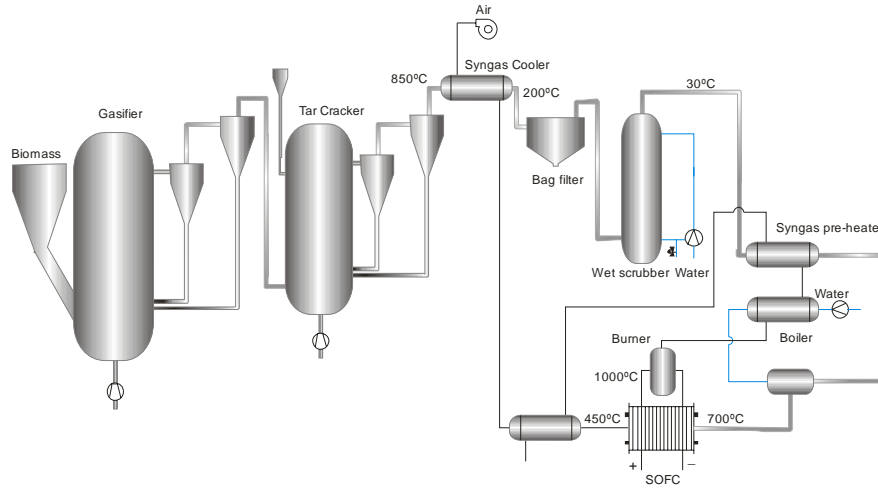


Figure 2 Schematically diagram of the SOFC system

3. Results

3.1 Gasification system integrated with FC type PEMFC

The results of the energy balance of the system with PEMFC are illustrated in figure 3. Had the pure hydrogen requirement for feeding of the PEMFC the system becomes complex with many energy losses. The decrease of the temperature of the synthesis gas of 200°C for 30°C in wet scrubber results in transference of 80 kW for the water, this energy is of low quality due to low final temperature of the water. An alternative to wet scrubbers could be the ceramic filters that work to a temperature of 400°C, however these filters still is in development phase.

A part of the synthesis gas enthalpy (850°C) is save in a heat exchanger to reheat the proper synthesis gas (pre-heater) until the temperature of 500°C so that it is possible to initiate the conversion of the CO (shift). Had the considerable amount of CO in the synthesis gas this conversion must be made in two stages, one in the high temperature reactor and another in the low temperature reactor. Being that the first reactor of shift must be cooled with air so that the temperature of the exit gas (shift gas) either of 250°C. In as the reactor of shift 250°C is that the shift reaction CO reaches the equilibrium. Heated air can be used for the burning of the residual gases of PSA system and the fuel cell (H₂, CH₄ and C₂H₄).

Shift gas presents minor energy content with relation to the synthesis gas in the exit of the gasifier, a time that the CO is oxidized and the hydrogen proceeding from the steam is not enough to keep the initial calorific power. The shift gas lower heating value was of 2.824 kJ/m³.

After to leave the reactor of shift 250°C shift gas must be cooled for 55°C in the condenser, removing and purging the humidity of the gas before system PSA.

For system PSA shift gas must be compressed the absolute pressure of 1000 kPa, the gases N₂, CO₂, C₂H₄ and CH₄ are adsorbed by the layers actives. As the system must be depressurized to liberate these gases, practically all the compression energy is lost, this constitutes the biggest expense of energy of the PEMFC generation system. The presence of a great amount of N₂ in the gaseous mixture proportionally demands a bigger volume for all the components of the system and greater energy consumption of compression. An alternative could be the gasification with indirect heating, that would eliminate the presence of N₂, however still would have the necessity of the use of the PSA for removal of the other gases.

In this paper it was considered that 100% of hydrogen of the gaseous flow in the PSA was recouped to feed the fuel cell. The electric power generated by the fuel cell was of 229 kW, being that 20% of the hydrogen that does not react (U_f = 80%) can be mixed to the residual gases of the PSA for steam generation for the shift reaction CO. Due to presence of great amount of inert gases (63% N₂ and 29% CO₂) the flame temperature of this residual gas the was calculated in 327°C. With the enthalpy and mass outflow of the combustion gas can be produced a mass outflow 524 kg/h of steam at 300°C and 1000 kPa. Being 31 kg/h used in shift reactor and 493 kg/h is available for co-generation.

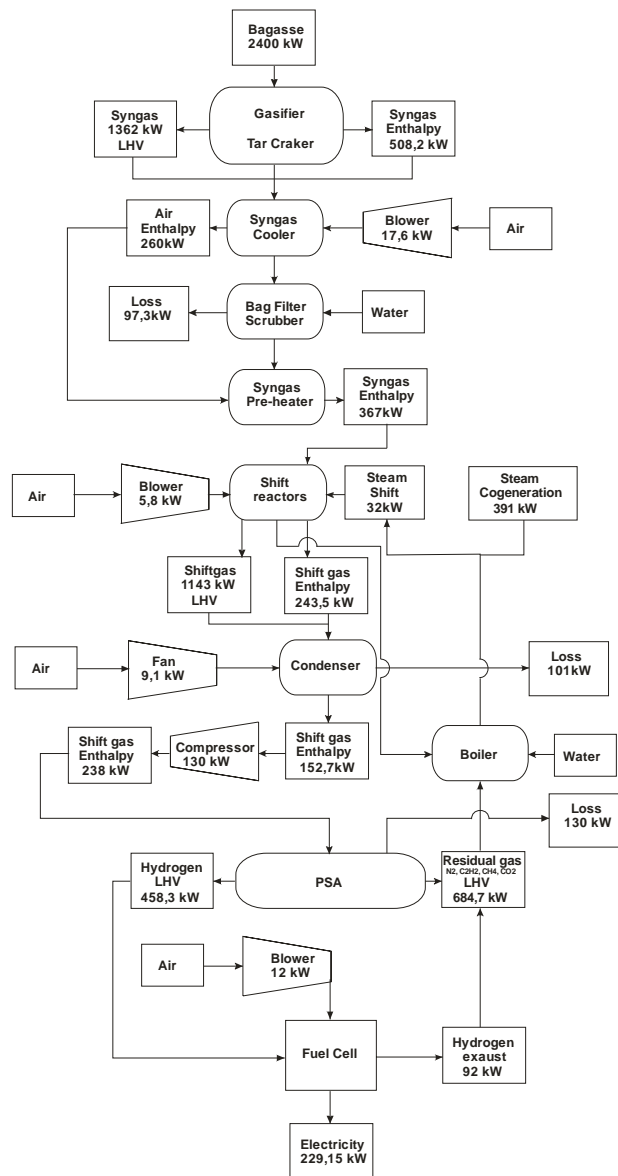


Figure 3 Energy balance of the system with PEMFC

Not being viable to carry through the methane reforming contained in the synthesis gas to produce more hydrogen, the electric efficiency of the PEMFC system is damage, a time that methane energy content is considerable, about 429 kW. For a methane reforming another reactor operating 900°C would be necessary, what it would excessively increase the complexity of the PEMFC system.

The electric efficiency of the PEMFC system, disrespecting the consumption of energy of ground handling equipments, in relation to the lower heating value of the synthesis gas was of 16,8%, and in relation to the lower heating value of the sugar cane bagasse it was of 9,5%.

The efficiency with co-generation was of 45 % in relation of the lower heating value of the synthesis gas and 25,8% in relation to the lower heating value of the sugar cane bagasse.

Had the low efficiencies calculated for the system integrated with PEMFC and its complexity, the fuel cell type PEMFC presents a low potential for integration with the biomass gasification.

3.2 Gasification system integrated with FC type SOFC

The results of the energy balance of the SOFC system are illustrated in figure 4. Had the high operating temperature of the SOFC (1000°C) it has one better integration with the biomass gasification; therefore this FC can operate directly with the synthesis gas. All the reagents (air, synthesis gas and water for internal reforming of the methane) must be preheated, air 450°C, the synthesis gas and the water at 700°C.

Had the gasification with oxygen the synthesis gas is free of nitrogen, its new composition is of 23% H₂; 29,1% CO; 8,5% CH₄; 38,3% CO₂; e 1,1% C₂H₄. The outflow of this gas is of 545 Nm³/h and an lower heating value of 9.153 kJ/Nm³. The advantage of the absence of nitrogen is the lesser volume of the equipment, as well as this gas it could influence negative in the efficiency of the SOFC and the generation system.

In the case of the SOFC system it would not immediately compensate the existence of a PSA before the fuel cell, therefore the electric efficiency of the system would be the same one calculated for the PEMFC. In this paper the calculated efficiency of the SOFC, operating with this synthesis gas, was of 38%. Oudhuis et. al. (2004) in its experimental results had reported an efficiency of 41% for a SOFC of 1 kW operating with a synthesis gas of similar composition to the gasification of the sugar cane bagasse, but it exempts of the gas ethylene (C₂H₄).

The electric efficiency of the fuel cell would be of 50% operating with pure hydrogen, this fall for 38% must the use of the CO as combustible and the CO₂ presence as inert gas, and of the C₂H₄. But it would not compensate to remove CO₂ of the gaseous flow, therefore it would also imply in the removal of the methane, what it would sufficiently compromise the electric efficiency of the SOFC system.

The electric power produced by the SOFC in this case were calculated in 532 kW. The exhaustion gases of the fuel cell understand the N₂, the C₂H₄, H₂, CO and also H₂O. The temperature of this gaseous flow is of 1000°C, with the burning of the combustible gases mixed to the inert gases this temperature increased for 1100°C. The enthalpy of this gaseous mixture was used to preheat the water for the methane internal reforming and the synthesis gas of until 700°C and the air of 200°C for 450°C. The final temperature of these exhaustion gases was calculated in 755°C, being that its enthalpy if directed for a HRSG Heat Recovery Steam Generation, it results in the steam production of 1.314 kg/h at temperature of 350°C and 2000 kPa. Of this form the SOFC system presents a good potential for co-generation.

The electric efficiency of the SOFC system in relation to the lower heating value of synthesis gas was of 38% and the electric efficiency with relation to the lower heating value of the sugar cane bagasse was of 22%.

The efficiency with co-generation in relation to the lower heating value of the synthesis gas was of 76,4% and the efficiency with relation to the lower heating value of the sugar cane bagasse was of 44%.

A considerable improvement in this system would be the use of an indirectly heating gasifier, not needing a PSA and, therefore diminishing the energy consumption.

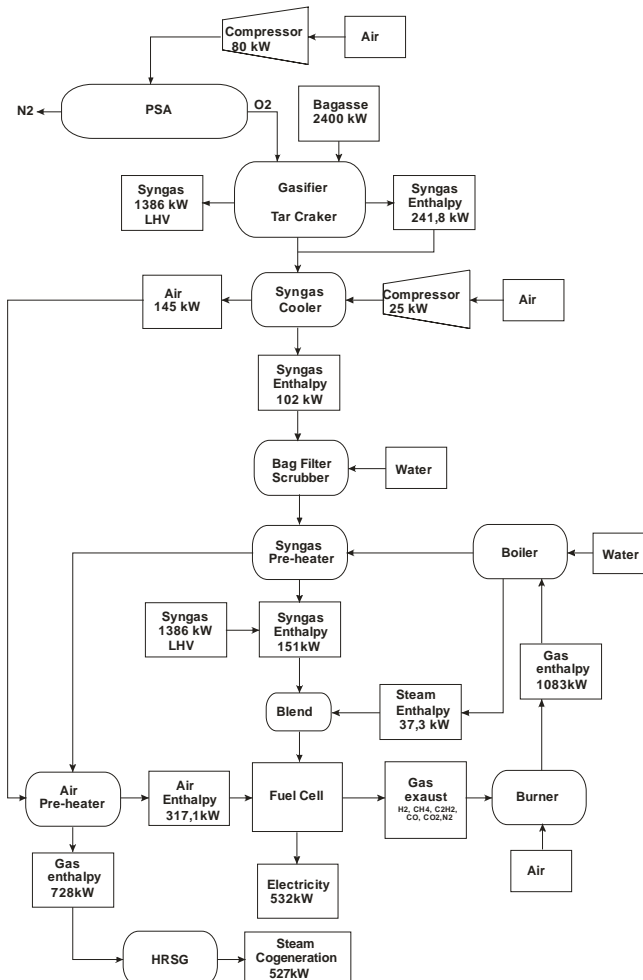


Figure 4 Energy balance of the system with fuel cell type SOFC

4. Conclusion

On the basis of the results of the energy analysis of the two fuel cell systems, conclude that the fuel cell type PEMFC does not present potential for the integration with the biomass gasification. The processing of the synthesis gas for the hydrogen separation consumes an amount of energy that makes impracticable the generation system.

On the other hand the fuel cell type SOFC presents great potential for the integration with the biomass gasification and co-generation. The consumption of energy for the PSA to get pure oxygen for the gasification is a disadvantage, but the job of the PSA can be discarded using itself a system of gasification with indirect heating. These systems of gasification already are being successfully tested in pilot plants around of the world.

5. Acknowledgements

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