The Sotacarbo gasification pilot platform: plant overview and recent experimental results

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Abstract

In the field of hydrogen production through coal gasification for distributed power generation, Sotacarbo is developing different research and development projects for the tuning of a coal-to-hydrogen process configuration. To this goal, a flexible pilot platform has been built in 2007-2008 and it is currently into operation. In particular, the platform includes a demonstration and a pilot air-blown fixed-bed gasifiers, the latter equipped with a flexible syngas treatment line for combined power generation and CO_2-free hydrogen production.

This paper presents a short description of the whole experimental equipment and summarises the main results obtained during about 1500 hours of experimental tests in the pilot unit.

Gasification performance with different operating conditions is also reported. In particular, a number of different fuels and fuel blends have been tested, including South African sub bituminous coal, Sardinian high sulphur coal, lignite from Alaska (which presents, at now, the best gasification performance) and wood chips from local forests. Moreover, the main performance of the syngas cleaning process is quickly discussed.

Finally, the very high efficiency of sulphur compounds removal through a zinc oxide-based hot gas desulphurization process suggested to evaluate the possibility to integrate the plant with a fuel cell system for a high efficiency combined heat and power (CHP) generation. The main results of this theoretical assessment, carried out by using a properly developed simulation model, are also reported in this work.

Keywords: *Coal and biomass gasification, Pilot plant, Hydrogen production, Molten carbonate fuel cell.*

1. Introduction

In this transition phase towards a sustainable worldwide energy system (mainly based on renewables and nuclear sources), fossil fuels (and coal in particular) will remain a significant source of energy for several decades [1-3].

Among clean coal technologies, coal gasification could represent a competitive option for power generation and also for chemicals or clean fuels production, with particular reference to hydrogen, universally considered one of the most promising energy carriers [4-5] and characterized by a worldwide production (18% from coal) greater than one billion of cubic meters per day [6-7]. Moreover, gasification processes can be easily integrated with pre-combustion CO_2 capture systems, typically more efficient and less expensive than the post-combustion processes [8-11].

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In this context, Sotacarbo is engaged in a series of research and development projects in order to develop and optimize a gasification process and an integrated syngas treatment line for CO_2-free power generation and hydrogen production from coal and biomass. To this aim, about 1500 hours of experimental tests have been performed, since June 2008, in a flexible pilot platform located in the Sotacarbo Research Centre, in Carbonia (South-West Sardinia, Italy). The platform includes a 1.3 m diameter demonstration unit and a 0.3 m diameter pilot unit, the latter equipped with a complete syngas treatment line for both power generation and hydrogen production.

The choice of pilot platform configuration is a compromise between the need to develop a gasification process for medium and small scale industrial applications and the interest in the development of coal-to-hydrogen integrated processes to be applied in large-scale power plants. In particular, the target of the gasification process (medium and small scale, up to 10-15 MW_{th}) led the choice of a fixed-bed, air-blown gasifier. As a matter of facts, these processes can be simply managed [12-13] and it is well known that the counter current fluid dynamics assure a higher efficiency with respect to other gasification technologies [14].

The Sotacarbo gasification technology allows to gasify different kinds of coal (including high sulphur low rank coals) and also biomass. Moreover, the flexible configuration of the pilot syngas treatment line allows to test and characterize some gas treatment processes and materials (solvents, sorbents and catalysts) for syngas desulphurization, water-gas shift, CO_2 removal, hydrogen purification and so on. These specific properties of the pilot unit are allowing Sotacarbo to provide technical support to third Companies to test specific fuels, materials and processes.

This paper reports a short description of the whole pilot platform (and, in particular, of the pilot unit), together with an overview of the main experimental results obtained with the most representative tested fuels. Moreover, a potential future integration of the pilot plant with an advanced syngas-feed molten carbonate fuel cell (MCFC) system for a combined heat and power (CHP) configuration has been analyzed by using the experimental results as input data of a properly developed simulation model.

2. An overview of the Sotacarbo pilot plant

The Sotacarbo pilot platform (figure 1) has been built up to test different plant solutions at different operating conditions; therefore, a very flexible and simple layout has been designed and constructed. Both demonstration and pilot plants are based on an up-draft, air-blown and fixed-bed gasification process, suitable to be fed with both coal and biomass.

Demonstration unit

The demonstration unit is based on a 1.3 m diameter gasifier, equipped with a manual coal charging system, a wet scrubber for dust and tar removal and a flare for syngas combustion.

For the feed of the gasifier, fuel is provided in big bags; every bag is drown out from the storage area by a heaver and, through a tackle, it is charged in a proper hopper in order to empty the bag itself. Then, fuel is drown out from this hopper and sent to the gasifier through four different injection points, in order to distribute the fuel as uniformly as

Figure 1. The overall Sotacarbo platform.

possible and to optimize the gasification process.

The fuel bed (which operates at about 0.11-0.14 MPa) is characterized by different operating zones, where the coal drying, devolatilization, pyrolisis, gasification and combustion processes take place. As fuel flows downwards, it is heated by the hot raw gas that moves upwards, coming from the gasification and combustion zones [15-16]. The gasification agents (air and steam) are introduced into the reactor near the bottom, below the fuel grate, so that they are pre-heated by cooling the bottom ash, which are removed through the grate itself.

Figure 2. Pilot gasifier.

In order to distribute the fuel as uniformly as possible, the reactor is equipped with a stirrer (internally cooled, in order to keep a low metal temperature), which is characterized by two degrees of freedom: an axial rotation and a vertical translation. Furthermore, the gasifier is equipped with a cooling water jacket, in order to operate an accurate temperature control.

The start-up of the gasifier is carried out by using a series of six ceramic lamps, located near the bottom of the fuel bed, which heat the fuel (initially wood pellets) in an inert atmosphere. The gasifier is equipped by a series of 36 thermocouples (6 sensors, disposed around the circular section of the reactor, in 6 different height levels) in order to have a detailed temperature profile into the reactor.

Pilot plant does not include a syngas desulphurization section (raw syngas is only sent to a wet scrubber, for tar and dust removal, and then it is directly burned in a flare); therefore, it can only be fed with fuels characterized by a sulphur content lower than 0.5-0.6 % (by weight).

Pilot Unit Gasification process

Due to its dimension, pilot gasifier (figure 2) is quite different from the demonstration unit. In particular: (i) primary fuel is charged through a single inlet point, (ii) the gasifier internal wall is covered with a refractory material, (iii) the reactor is currently not equipped with the intercooled stirrer and (iv) the gasification agents (air, eventually enriched with oxygen, and steam) can be pre-heated up to about 250 °C. Moreover, temperature profile into the reactor can be determined through a probe, located near the reactor vertical axis and equipped with a series of 11 thermocouples, and through a series of other 37 thermocouples located near the reactor's wall and in the grate.

The manual controlled fuel feeding system is identical with respect to the demonstrative plant and an extractor fan, which serves both pilot and demonstration gasifiers, allows the extraction of dust during coal handling and charging phase.

Dust and tar removal system

As shown by figure 3, raw syngas from the gasification process is sent to an integrated skid which includes a wet scrubber, a first cold gas desulphurization stage and an electrostatic precipitator (ESP).

In particular, wet scrubber reduces syngas temperature from 150-300 °C (depending on the particular operating conditions) to about 50 °C and operates a primary dust and tar separation. An electrostatic precipitator (ESP) allows, if necessary, to complete particulate and tar removal. Due to the need to use coals with very high sulphur contents and to protect the electrostatic precipitator by the effects of acid atmosphere, a first cold gas desulphurization stage (which typically uses an aqueous solution of sodium hydroxide as solvent) is installed upwards of the ESP.

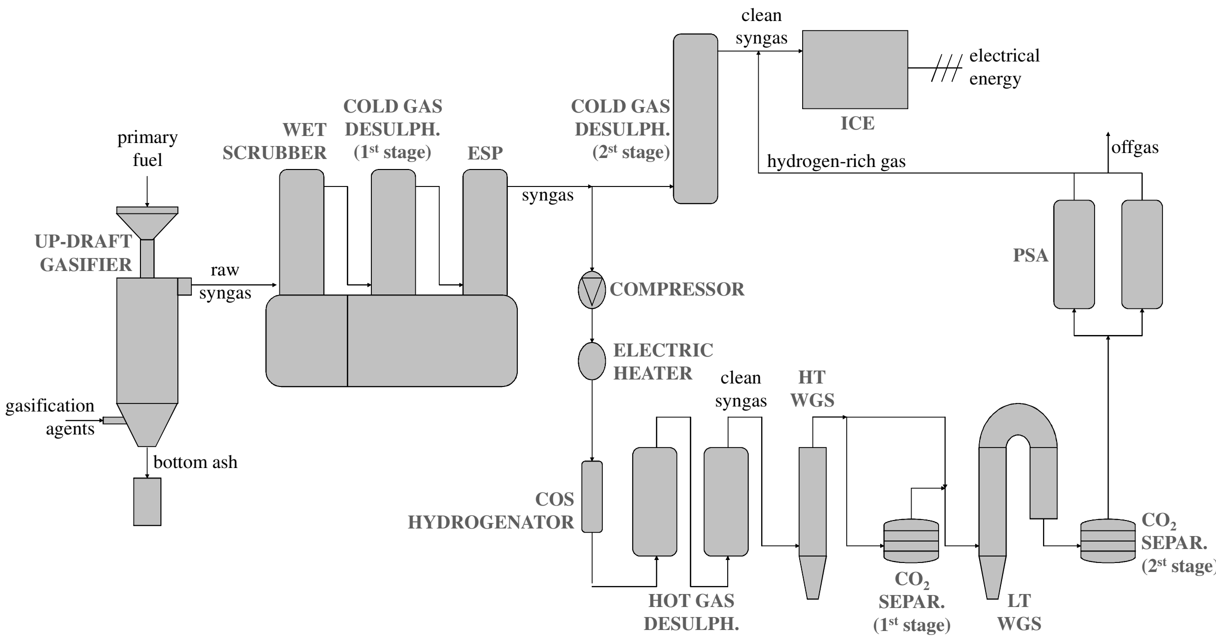

Figure 3. Pilot plant simplified scheme [17].

Downstream of the ESP, syngas can be sent to the power generation line; moreover, depending on the goals of each experimental test, a portion of syngas (20-25 Nm^3/h) can be sent to the hydrogen production line.

<u>*Power generation line*</u>

Power generation line is constituted by the second cold gas desulphurization stage, directly followed by an internal combustion engine (ICE), characterized by a nominal power output of about 24 kW, fed with clean syngas, eventually enriched in hydrogen.

In particular, the second cold gas desulphurization stage is a packed column in which hydrogen sulphide is chemically absorbed through an aqueous solution of sodium hydroxide and hypochlorite [18]. During several specific experimental tests, the column has been also used with other solvents such as methildiethanolamine (MDEA) for H_2S absorption or with monoethanolamine (MEA) for carbon dioxide capture.

A two-chamber gasometer (with an overall internal volume of 11.3 m^3) has been recently installed to overcome problems of pressure variability and low syngas mass flow at the inlet of ICE and to ensure a constant electric energy production.

<u>*Hydrogen production line*</u>

Hydrogen production line includes a compressor (just to win the pressure drops through the downwards equipment) followed by an electric heater, a dry hot gas desulphurization process, an integrated water-gas shift (WGS) and CO_2 absorption system and a hydrogen purification section.

In particular, hot gas desulphurization process operates at about 300-500 °C and includes three main components: a catalytic filter for COS conversion and two H_2S adsorbers. In the catalytic filter, the small amount of carbonyl sulphide contained in syngas is converted in H_2S through the hydrogenation process, promoted by Ni-MoO_3/Al_2O_3 catalyst [19]. On the other hand, the two hydrogen sulphide absorbers (figure 4) are disposed in lead-leg configuration and filled with a zinc oxide-based sorbent [20-22]. In particular, zinc oxide (ZnO) reacts with H_2S producing zinc sulphide and steam [23-25].

Clean syngas from hot gas desulphurization system, with a H_2S concentration typically lower than 1 ppm (by volume), is sent to a double stage water-gas shift (WGS) process, with an intermediate and a final CO_2 absorption system. In particular, WGS process takes place into two reactors operating at high temperature (HT, between 300 and 450 °C) and low temperature (LT, about 250 °C), respectively. Both conventional and advanced catalysts have been tested during the experimental campaigns [17]. Carbon dioxide absorption takes place into two identical bubbling reactors (figure 5), in which syngas is injected through 40 diffusers based on ceramic membranes and reacts, at about 30 °C and atmospheric pressure, with amine-based solvents.

Figure 4. Hot gas desulphurization system.

An amine regeneration unit has been also installed to study the performance of thermal CO_2 desorption of exhaust chemical solvents (mainly MEA). The column, which can operate in batch or continuous modes, is equipped with an electrical reboiler (which operates at 120-150 °C), a condenser, a mist separator to split CO_2 gas from residual water and solvent vapors and a series of heat exchangers to preheat rich solvent and to cool lean solvent.

Finally, hydrogen purification section is based on the pressure swing adsorption (PSA) technology, which is widely common in the industrial applications due to its low costs [26]. In particular, PSA is composed by a simple double-stage process based on carbon molecular sieves.

The size of the secondary syngas treatment line, even if much smaller than the size of commercial scale plants, has been chosen in order to give reliable experimental data for the scale-up of future plants. Moreover, with the goal to ensure a full plant flexibility, as well as to simplify the management of the experimental pilot plant, the different cooling and heating devices are not fully integrated.

Control system and data collection

In order to support the experimental tests, pilot plant is equipped with a control and sampling system which allows the monitoring of the main operating parameters (such as pressures, temperatures, volume flows and so on) and the evaluation of the process performance.

Syngas composition is measured by three different systems: (i) a double real-time oxygen analyser, (ii) a micro gas-chromatograph and (iii) a real-time monitoring system. In particular, the two real-time oxygen measurers in raw syngas play a double role of safety control, to avoid the formation of explosive atmosphere, and performance indicator of the gasification process [27-28]. Upstream and downstream of each plant component, a sampling outlet has been located in order to operate

Figure 5. CO_2 absorbers.

syngas analysis through both a gas chromatograph (which evaluates, every three minutes, the concentration of CO_2, H_2, O_2, CO, CH_4, N_2, H_2S, COS, C_2H_6, C_3H_8 in the selected stream) and a new integrated analyzer (which gives the real-time composition of every stream by using different methods, such as infrared detection for CO, CO_2 and CH_4, thermal conductivity for H_2, paramagnetic analysis for O_2 and UV detection for H_2S).

Table 1. Primary fuels characterization.

	Bitum. coal South Africa	*Sulcis Italy*	*Usibelli Alaska*	*Wood chips Italy*
Proximate analysis (% by weight)				
fixed carbon	72.58	40.65	31.33	18.30
moisture	3.64	7.45	17.64	7.70
volatiles	8.81	40.45	41.00	73.63
ash	14.97	11.45	10.02	0.37
Ultimate analysis (% by weight)				
total carbon	75.56	66.49	48.56	49.95
hydrogen	3.86	6.18	5.96	6.14
nitrogen	1.40	1.41	0.50	0.11
sulphur	0.57	7.02	0.18	0.00
oxygen	n.a.	n.a.	17.14	35.74
moisture	3.64	7.45	17.64	7.70
ash	14.97	11.4	10.02	0.37
Thermal analysis (MJ/kg)				
LHV	27.18	21.07	17.75	17.25

Finally, the plant has been recently equipped with a tar sampling and analysis system, in order to evaluate, through a proper gas chromatograph, the content and the composition of the main hydrocarbon components in raw syngas.

3. Pilot plant performance

As mentioned, pilot plant has been tested for about 1500 hours of experimental tests since July 2008. The performance analysis here reported comes from the processing of the experimental data automatically collected by the system.

Gasification performance

The experimental tests in the pilot plant have been operated using different kinds of fuels. In particular, the results here reported are referred to the gasification of (i) a low sulphur South African coal, (ii) a mixture of the latter (80%) with a high sulphur local coal (from the Sulcis coal mine, located near the Sotacarbo pilot platform), (iii) a lignite from Alaska (Usibelli coal mine) and (iv) a local biomass. The latter is chipped stone pine (pinus pinea) wood from local forests, supplied by the Sardinian Regional Authority for Forests.

The proximate, ultimate and thermal analyses of these fuels, determined in the Sotacarbo laboratories (according to the international standard procedures), are shown in table 1 (where LHV is the lower heating value of each fuel).

The performance of the gasification process with the previously described feedstock is summarized in table 2. The reported results are typically averaged during at least six hours of steady-state operation of the reactor [29].

Table 2. Typical gasification conditions and performance [29].

	S. African coal	*80% S.Afr. 20% Sulcis*	*Usibelli coal*	*Wood chips*
Operating parameters				
fuel consumption (kg/h)	8.0	10.5	24.0	12.0
air mass flow (kg/h)	36.8	41.2	57.6	11.3
steam mass flow (kg/h)	3.7	7.8	3.7	0.0
Raw syngas composition (molar fractions, dry basis)				
CO	0.1807	0.1772	0.2368	0.2207
CO_2	0.0947	0.0969	0.0771	0.0797
H_2	0.1889	0.2149	0.1779	0.3342
N_2	0.5128	0.4780	0.4729	0.3418
CH_4	0.0151	0.0151	0.0173	0.0119
H_2S	0.0003	0.0006	0.0002	0.0000
COS	0.0001	0.0001	0.0001	0.0000
O_2	0.0074	0.0172	0.0176	0.0117
Raw syngas properties (dry basis)				
mass flow (kg/h)	46.83	54.84	79.67	23.31
volume flow (Nm^3/h)	42.90	51.49	72.90	25.48
LHV (MJ/kg)	4.50	4.83	5.14	7.49
specific heat (kJ/kg K)	1.23	1.27	1.23	1.47
outlet pressure (MPa)	0.14	0.14	0.14	0.14
Main gasifier performance				
maximum temp. (°C)	1034	1050	993	730
cold gas efficiency	96.93%	97.20%	96.13%	84.33%
gasifier yield (Nm^3/kg)	5.36	4.90	3.04	2.12

As expected, due to its high reactivity and high volatile content, Usibelli coal allows to maximize the syngas production: among the number of fuels tested in the plant, it presents, at now, the best performance. On the contrary, the low reactive South African coal appears not completely suitable for the gasification in the Sotacarbo air-blown process (since it operates at about atmospheric pressure); this is confirmed by the relatively high carbon content in the discharged ash during the experimental tests with South African coal. Pure Sulcis coal is quite similar to Usibelli lignite in terms of volatiles and ash content, but its very high sulphur percentage does not suggest the use as single fuel in a commercial application: this justifies the choice to mix Sulcis coal with low sulphur South African coal. Finally, the performance reported for wood chips gasification comes from an extrapolation of the experimental results of a preliminary run: the process should be optimized in order to improve the syngas production and stabilize the operating conditions [29].

Raw syngas composition is strongly influenced by fuel properties and gasification parameters [30]. In particular, raw syngas from South African coal presents a very low content of sulphur compounds: 274.3 ppm of H_2S and 100.9 ppm of COS, by volume. When a mixture of South African coal with 20% of Sulcis coal is used, H_2S content increases (634.4 ppm), whereas COS content remains about the same (126.3 ppm). When Usibelli coal is gasified, H_2S and COS concentrations are very low (241.0 and 61.5 ppm, respectively) in raw syngas. Finally, sulphur compounds concentrations are negligible for wood chips gasification, due to the absence of sulphur in the considered biomass.

Fuel petrology

In addition to fuel characterization in terms of syngas production and properties, it is currently under evaluation a different approach to predict the suitability of a fuel to be gasified in an atmospheric fixed-bed up-draft reactor, such as the Sotacarbo pilot unit. This approach, based on the evaluation of the fuel reactivity, has been successfully assumed by Thimsen et al. [31] during an experimental campaign carried out in early 80s in a fixed-bed gasification plant characterized by similar operating conditions.

Fuel reactivity can be determined through the specific gasification rate (SGR, expressed in $kg/m^2{\cdot}h$), defined as the amount of gasified fuel (kg/h) divided by the area (m^2) of the horizontal section of the fuel bed. For fixed-bed gasifiers, SGR corresponds to the so-called grate loading (GL), defined as the amount of fuel gasified per square meter of grate area.

According to these definitions, SGR evaluated for the four different feedstock reported in table 2 amounts to 113, 148, 339 and 169 kg/m^2·h, respectively. This confirms the higher reactivity of Usibelli lignite with respect to the other tested feedstock.

Table 3. Coals classification.

	S. African coal[1]	*Sulcis coal*[2]	*Usibelli coal*[3]
Macerals content (% by weight)			
vitrinite	25.8	71.2	74.0
inertite	60.0	5.6	7.0
liptinite	4.2	11.6	14.0
minerals	10.0	11.6	5.0
vitrinite reflectance index	0.7%	0.5-0.7%	0.3-0.6%

Notes:
1 Source: Ghetti et al., 2000 [32].
2 Source: Ciccu et al., 2010 [33].
3 Sources: Walsh et al., 1995 [34]; Hankinson, 1965 [35].

In case of coal gasification, the reactivity can be theoretically correlated with the petrographic structure of coal itself, with specific reference to maceral content. In particular, table 3 reports the maceral content of the considered coals, in terms of vitrinite, inertite, liptinite and minerals, together with the vitrinite reflectance index.

Vitrinite is the most homogeneous maceral, which mainly contributes to the formation of the so-called cleats, sort of cracks of the particle surface which increase the structure permeability and porosity, promoting char reactivity. On the contrary, inertite presents a dense and amorphous structure, and its high concentration in coal reduces fuel reactivity. Finally, a high liptinite content promote the production of gas hydrocarbons and tar and conditions coal LHV. Vitrinite reflectance index in oil can be used as an indicator of maturity in hydrocarbon source rocks and it conditions the coal rank. It can also be used as reference to predict the behavior of coal during gasification (low values of this index typically correspond to high reactivity of coal).

<u>*Syngas cleaning performance*</u>

As reported above, fly ash and tar removal takes place in both wet scrubber and electrostatic precipitator, which assure very low outlet concentrations of both particulate and tar.

Table 4 shows the typical clean syngas properties and composition at the outlet of hot gas desulphurization system, being the first cold gas desulphurization stage not operative due to the relatively low H_2S and COS concentrations in raw syngas.

It is important to underline that, as mentioned, the hot gas desulphurization system allows to achieve an overall sulphur compounds (H_2S and COS) concentration typically lower than 1 ppm (by volume) for all

Table 4. Typical syngas composition downwards of HGD.

	S. African coal	*80% S.Afr. 20% Sulcis*	*Usibelli coal*	*Wood chips*
Clean syngas properties				
Mass flow (kg/h)	50.13	58.78	85.23	25.28
Volume flow (Nm^3/h)	47.02	56.43	79.88	27.94
LHV (MJ/kg)	4.20	4.50	4.78	6.90
Pressure (MPa)	0.140	0.140	0.140	0.140
Temperature (°C)	400	400	400	400
Syngas composition (molar fractions)				
CO	0.1649	0.1618	0.2161	0.2013
CO_2	0.0864	0.0884	0.0703	0.0727
H_2	0.1722	0.1960	0.1622	0.3048
N_2	0.4678	0.4362	0.4314	0.3117
CH_4	0.0138	0.0138	0.0158	0.0109
H_2S	0.0000	0.0000	0.0000	0.0000
COS	0.0000	0.0000	0.0000	0.0000
O_2	0.0068	0.0157	0.0161	0.0107
H_2O	0.0881	0.0882	0.0881	0.0881

the four considered feedstocks. Obviously, this system is unessential when only wood chips are used as fuel in the gasification process.

4. Potential future developments: integration with a MCFC system

Currently, Sotacarbo is engaged in a number of analyses with the aim of optimize the gasification process for different kinds of fuels or fuel blends and to analyze innovative configurations for power generation and hydrogen production. In particular, a preliminary analysis has been started to evaluate the possibility to apply the Sotacarbo coal and biomass gasification technology for high efficient power generation in a small-scale combined heat and power (CHP) industrial system by a potential integration of the gasification process itself with a molten carbonate fuel cell (MCFC).

Methodology and plant configuration

Mass and thermal balances of the gasification and syngas treatment processes have been evaluated on the basis of the experimental data collected during gasification and hot gas desulphurization tests. On the other hand, the performance of the MCFC stack has been assessed by a simulation model, based on thermodynamic-electrochemical analysis at steady-state operating conditions. The model has been developed by Sotacarbo in close cooperation with the University Cagliari (Department of Mechanical, Chemical and Materials engineering) and it is described in a previous work [36].

In particular, this analysis considers the same four gasification conditions reported in table 2. Raw syngas is assumed to be washed in the wet scrubber and fully sent to the catalytic COS hydrogenation system followed by the zinc oxides-based hot gas desulphurization process, with the final properties reported in table 3. Finally, clean syngas is heated up to 650 °C and sent to the anode of the MCFC stack, which operates at 0.137 MPa. The fuel cell cathode is fed with a gaseous stream composed by N_2, CO_2 and O_2 (55, 30 and 15% by volume, respectively).

Inside the fuel cell, which performance are considerably affected by operating temperature and pressure [36-37], the hydrogen flow rate decreases in the flow direction as it is consumed by anode reactions. However, hydrogen is produced by both water-gas shift and methane reforming reactions; consequently, change in hydrogen flow rate becomes slower. Carbon monoxide also decreases along the flow direction as a result of the balance between reforming and shift reactions, which produce and consume it, respectively. Finally, methane is consumed while an inverse trend can be observed for the carbon dioxide. In the cathode, oxygen and carbon dioxide flow profiles are similar, both decreasing in flow direction. These profiles are in good agreement with the chemical process taking place in the cathode, in which both oxygen and carbon dioxide are consumed [29].

Fuel cell performance

Table 5 reports the energy balance of the fuel cell stack for the four considered gasification conditions. Sensible heat (H_{th}) released by the MCFC system has been evaluated by the following energy balance [38]:

$$P_{in} = P_{el} + H_{loss} + H_{inc} + H_{th}$$

where P_{in} is the clean syngas combustion potential (mass flow multiplied by the lower heating value), P_{el} is the released electric power, H_{loss} is the heat loss due to

Table 5. MCFC energy balance [29].

	S. African coal	*80% S.Afr. 20% Sulcis*	*Usibelli coal*	*Wood chips*
P_{in} (kW)	58.5	73.6	113.2	48.5
power P_{el} (kW)	19.9	23.5	36.7	15.5
H_{loss} (kW)	2.9	3.7	5.7	2.4
H_{inc} (kW)	22.0	27.7	40.6	19.9
H_{th} (kW)	13.6	18.8	30.2	10.7

irradiation, prefixed equal to 5% of inlet energy flow [38] and H_{inc} is the potential energy of combustion available in the outlet MCFC exhaust (all the terms are expressed in kW).

In the pilot plant CHP configuration, in which the best performing Usibelli lignite feedstock is considered, the MCFC system can be fed with a syngas flow of about 80 Nm^3/h, which gets a combustion potential (P_{in}) of 113.2 kW. In this conditions, a MCFC electrical efficiency of about 32.4% has been calculated, together with a potential cogeneration (heat and power) efficiency of 59.1%. Considering the integration between gasification, syngas treatment and power generation sections, the overall CHP configuration could present an electrical efficiency of about 31.5% and a cogeneration efficiency of 57.3% [29].

A further improvement of these performance can be achieved by the integration of the MCFC system with a burner to recover the residual energy content (H_{inc}) in the exhaust gas. In particular, MCFC anode spent gas can be recycled to the burner for the combustion of residual hydrogen, carbon monoxide and methane. At the same time, a partial flow of exhausts at the exit of burner can be recycled to supply MCFC inlet cathode with the necessary flow of CO_2. These integrations are currently under evaluation.

5. Conclusions

The about 1500 hours of experimental tests carried out in the flexible Sotacarbo pilot platform allowed to optimize gasification process and syngas treatment sections in different operating conditions and with different kinds of fuels. The gained experience and the high plant flexibility allow Sotacarbo to use the platform to develop some research projects and to provide technical support to several Companies for the characterization of fuels, processes and materials.

Among the different tested fuels, the high reactive lignite from Alaska presented, at now, the best gasification performance, with the production of about 73 Nm^3/h of raw syngas, characterized by a lower heating value of 5.14 MJ/kg. This performance is mainly allowed by the high volatile content of the Usibelli lignite, which promotes a quick and efficient conversion of the primary fuel. As expected, the gasification performance decreases when less reactive feedstock is used, in particular when only South African coal is fed to the reactor. Moreover, due to its low energy density, the gasification of wood chips does not allow a high syngas production.

The high efficient hot gas cleaning system, which operates COS hydrogenation and H_2S adsorption by using zinc oxides-based sorbents, allows a very clean syngas production, with a final concentration of sulphur compounds typically lower than 1 ppm by volume (even if high sulphur coals are gasified). This performance suggested to preliminarily analyze, by using a properly developed simulation model, the possibility to integrate the Sotacarbo pilot plant with a MCFC system, directly feed with clean syngas, to obtain an innovative CHP plant configuration. The analysis shows that the air-blown gasification of about 24 kg/h of Usibelli could allow the production of 36.7 kW of electrical energy and 30.2 kW of sensible heat. Therefore, whereas the single MCFC system presents an electrical efficiency of 32.4% and a cogeneration efficiency of 59.1%, the overall CHP configuration could present an electrical efficiency of about 31.5% and a cogeneration efficiency of 57.3%.

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