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Performance Analysis of Integrated Systems Based on MHD Generators

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Abstract

Magnetohydrodynamic (MHD) power generation is considered an interesting energy conversion system because converts thermal energy into electrical energy without mechanically moving parts. In an MHD generator, a thermal plasma is moving across a magnetic field generating electric power. The heat source required to produce the high-speed gas flow can be supplied by the combustion of a fossil fuel or by using renewable source such as solar energy.

The MHD efficiency is usually less than the conventional energy conversion systems (i.e. gas turbine combined cycle, steam power plant) but the availability of thermal power at high temperature can allow plant configurations with high overall efficiency.

In this paper two plant configurations based on open-cycle MHD generators fed with coal are presented. The first one is a conventional configuration in which the plasma gas is the products of direct combustion of coal. The second one can be considered an advanced type because the working fluid is the combustion exhausts of syngas generated from coal gasification. In order to evaluate the energy suitability of the proposed systems, a performance analysis has been carried out by means of numerical modeling. Therefore, the operating conditions and the plant configurations for an efficient recovery of the thermal energy available from the MHD exhausts have been defined by a sensitivity analysis carried out varying the preheating temperature of air (or enriched air) sent to the combustion chamber.

Results show that high system efficiencies (up to 60%) can be achieved by using the syngas due to a better heat recovery in the high temperature region.

Keywords: Magnetohydrodynamic power generator; system efficiency; coal; gasification; plasma

1. Introduction

The energy demand is almost completely satisfied by fossil fuels. This involves environmental issues regarding not only the harmful pollutants such as SO_x, and particulate matter (local pollution), but also the greenhouse gases,

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especially CO_2. Moreover, the difficulties of large-scale use of alternative options, like renewables, implies the need to carefully study more efficient and clean technologies to employ fossil energy while avoiding greenhouse gas emissions [1-4].

Coal will last for some centuries and its distribution on the Earth is not so concentrated as that of oil and natural gas, so that its cost will remain more stable and competitive for a long time. However, coal is the fossil fuel with the highest content of carbon and therefore the conversion efficiency is also important to reduce the carbon dioxide emissions. In the near term, advanced technologies that increase the power generation efficiency for new plants and technologies to capture carbon dioxide from industrial and power plants are being developed. In the longer term, the goal is to increase energy plant efficiencies and reduce both the energy and capital costs of CO_2 capture and storage.

Magnetohydrodynamic (MHD) power generation has been studied as a novel power plant due to its advantage of high-efficiency with high-working temperatures [5-16]. In an MHD generator, a thermal plasma is moving across a magnetic field generating electric power [5]. Because no mechanically moving parts are involved in the high temperature units in an MHD cycle, the MHD generator has the thermodynamical benefit that the maximum working temperature is not constrained by the mechanical strength of materials, but rather by the compatibility with high temperature and high heat flux environments [5,6].

Open-cycle and closed-cycle MHD generators are the two basic types of MHD systems under consideration, classified on the basis of the working fluid and the heat source [6-14]. Open-cycle MHD generators are feeding with combustion products (seeded by alkaline compounds such as potassium carbonate to improve their conductivity) and operate at maximum temperatures of 3000 K [6,9,11-13], whereas in the closed-cycle MHD generators an inert gas, which is heated in a high temperature heat exchanger of the ceramics pebble or cored-brick type and seeded with an alkaline metal such as cesium vapor, is the plasma working fluid [6].

In this paper two plant configurations based on open-cycle MHD generators fed with coal are presented. The first one is a conventional configuration in which the plasma gas is the product of direct combustion of coal. The second one can be considered an advanced type because the working fluid is the combustion exhausts of syngas generated from coal gasification. In order to evaluate the energy suitability of the proposed systems, a performance analysis has been carried out by means of numerical modeling.

2. The Power Plant Configurations

The plant configurations studied are:

- The conventional CF-MHCC (Coal Fired MagnetoHydrodynamic Combined Cycle) based on a MHD generator integrated with a steam turbine power plant;
- The advanced IG-MHCC,A (Integrated Gasification MagnetoHydrodynamic Combined Cycle) based on a MHD generator integrated with a steam turbine power plant;
- The advanced IG-MHCC,B in which the MHD generator is integrated with a steam turbine power plant and a closed gas turbine cycle fed with nitrogen.

The steam turbine power plant is a two pressure level system whose working parameters are the same for all configurations. The ultimate analysis and heating values of the coal (Illinois #6) feeding the conventional and advanced plants are reported in table 1.

Table 1. Ultimate Analysis and heating values of Illinois #6

Coal Illinois #6	Ultimate analysis (Wt %)
C	63.75
H	4.5
N	1.25
Cl	0.29
S	2.51
O	6.88
Moisture	11.12
Ash	9.7
HHV (MJ/kg)	27.13
LHV (MJ/kg)	25.88

2.1. The conventional configuration: CF-MHCC plant

With reference to Fig.1, the coal is sent to the combustion chamber (CC) that is fed by air enriched with oxygen (generated in the Air Separation Unit) to reach the temperature for plasma generation. The combustion products, seeded with potassium carbonate in order to increase the plasma conductivity, enter the MHD generator where electrical power is produced and leave the system at high temperature and pressure close to the atmospheric one. The thermal power available from the MHD exhausts is used to generate steam and, in order to enhance the overall system efficiency, to preheat the combustion air in a heat exchanger (HEX).

In order to optimize the heat recovery of the MHD exhausts, it is suitable to place the air preheater just downstream of the MHD diffuser. However, to avoid the slag condensation and solidification that may take place in regions at temperatures below about 1300°C, the highest attainable air temperature is likely to be around 800°C [6]. Therefore, primary heat regeneration is performed by high pressure steam generation with a radiant-type boiler at the highest temperature region. The heat recovery is completed in the Heat Recovery Steam Generator (HRSG) where low pressure steam is produced.

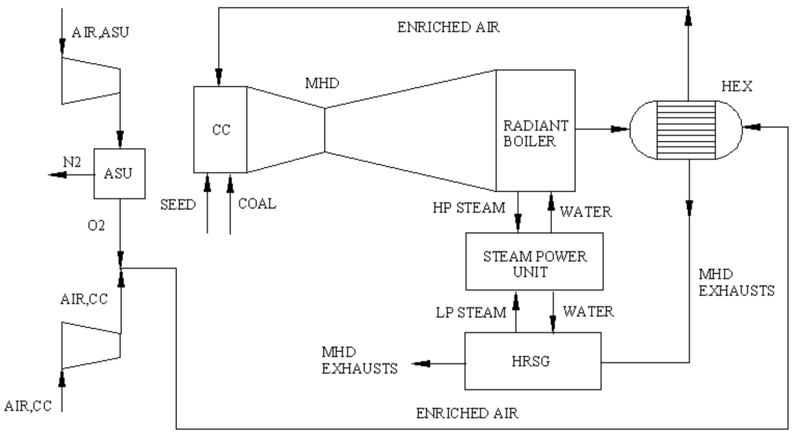

Fig. 1.CF-MHCC plant lay-out

2.2. The advanced configurations: IG-MHCC,A and IG-MHCC,B plants

The IG-MHCC,A plant, shown in Fig.2, consists of a gasification island where coal is converted into a synthesis gas by using oxygen and steam and a power island based on the MHD generator combined with a steam power unit.

The main components of the gasification island are the Air Separation Unit (ASU), the Fuel Processor Reactor (GASIFIER) supposed to be an entrained bed pressurized type, the Hot Gas Cleanup Unit (HGCU) where the acid gas (H2S, HCl) are removed at about 870°C [17]. In order to achieve the operating temperature of the HGCU unit the syngas coming out from the gasifier is cooled in a heat exchanger (HEX) by generating the superheated steam for the gasification reactions and then expanded in a turbine (EXPANDER) up to the operating pressure of the combustion chamber of the MHD generator. As in the CF-MHCC configuration, the combustion products are seeded with potassium carbonate to improve their conductivity, enter the MHD generator where the thermal energy is converted in electricity and leave the unit at high temperature and pressure close to the atmospheric one. The thermal power available from the MHD exhausts allows to preheat the combustion air (in the high temperature heat exchanger, HTHE) and to generate steam (in the heat recovery steam generator, HRSG) feeding the steam power unit.

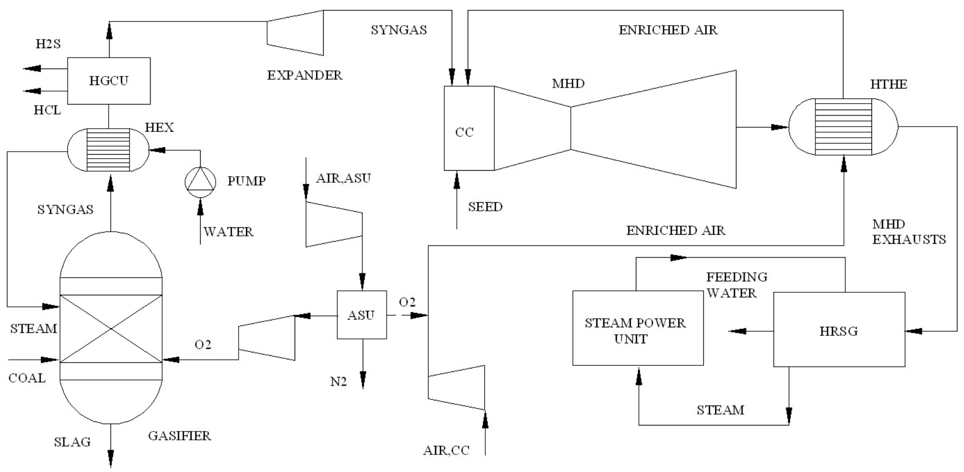

Fig. 2. IG-MHCC,A plant lay-out

It should be noted that the HTHE is placed just downstream the MHD diffuser, because no slag is involved. Therefore, the combustion air can be preheated up to 1800°C by a regenerative air heater with a corundum-based matrix [6].

In order to improve the heat recovery of MHD exhausts a closed gas turbine cycle has been also introduced in the plant configuration (IG-MHCC,B) shown in Fig.3.

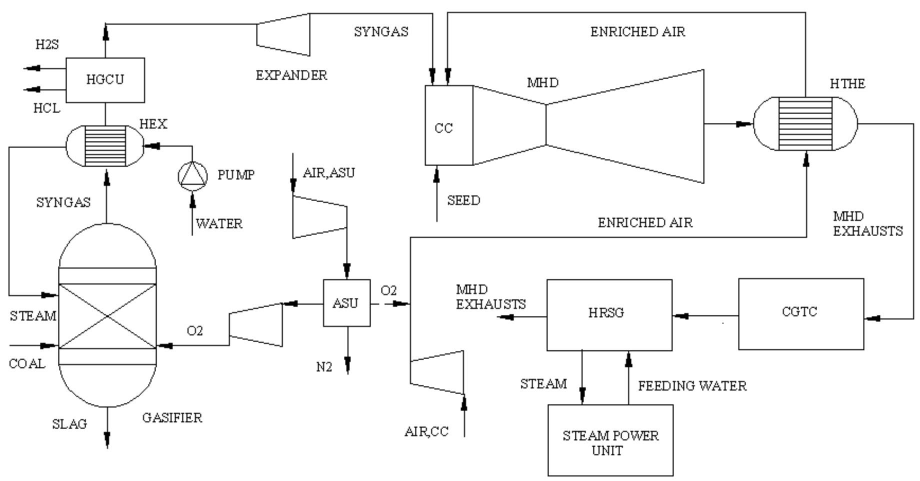

Fig. 3. IG-MHCC,B plant lay-out

3. The systems modeling

The power plants analysis has been performed by developing an integrated model between the thermochemical and thermodynamic models, needed to characterize mass and energy balances of each system component such as combustion chamber, gasifier, turbines, heat exchangers, and the electro-magnetic equations needed to solve the energy balance in the MHD generator.

Therefore, the gasifier is simulated considering the chemical equilibrium that is widely employed to study high temperature (>1000°C) gasification processes. The non-stoichiometric approach in which the equilibrium composition is found by the direct minimization of the Gibbs free energy for a given set of species and without any specification of the possible reactions taking place in the system [1,2], is chosen to define the syngas composition.

On the basis of coal composition reported in table 1, the species considered are CH_4, C_2H_6, C_2H_4, H_2, CO, CO_2, H_2O, H_2S, HCl, O_2, N_2, char (C) and tar as $C_{14}H_{10}$. The Peng-Robinson equation of state modified with the Boston-Mathias alpha function has been used to predict the thermodynamic properties of the material streams.
The air separation unit and the hot gas clean-up unit are performed by defining black-box models. Thus, in the ASU a 95% oxygen purity is assumed, whereas the acid gas removal efficiency is set to 98% according with literature data [17].

Heat and material balances of the power plants, as well as their performances, have been calculated by thermodynamic models developed using a fully-flexible modular code which allows to simulate thermal power plants (steam power plants, gas turbines, combined cycles etc.) in design and off design mode [18].

3.1 The MHD generator model

The MHD generator consists of a combustion chamber in which, in order to reach the temperature for plasma generation, the feeding fuel is oxidized by air (or air enriched with oxygen) and seeded to increase its conductivity, a nozzle where the plasma is accelerated up to the specified Mach number, the MHD duct (immersed in a magnetic field and equipped by electrodes placed on walls parallel to the magnetic field itself) where the plasma is expanded and the electric power is extracted, and a diffuser in which the kinetic energy of the plasma is converted to the energy pressure to achieve the required outlet conditions. Figure 4 shows a schematic of the MHD generator.

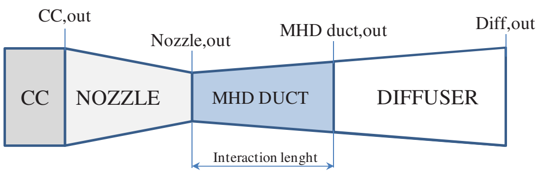

Fig. 4. Schematic of MHD generator

The combustion chamber is modelled as a stoichiometric reactor in which the complete oxidation of reactant species is assumed. In order to achieve the specified outlet temperature the amount of oxidant is calculated by material and energy balances.

If there is no cooling of the system walls, thermodynamic transformations inside the nozzle and inside the diffuser could be considered isentropic. The relationships between the extreme states of these transformations are those that exist between stagnation and static conditions:

$$\frac{T_0}{T} = \left(1 + \frac{\gamma - 1}{2} M^2\right) \tag{1}$$

$$\frac{p_0}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{2}$$

where T (K) and p (Pa) are the plasma temperature and pressure respectively, γ is the ratio between specific heats at constant pressure and volume, M is the Mach number of the plasma.

For the MHD duct, assumed to be an ideal segmented Faraday generator, considering a 1D approach, the governing equations can be written as [5,15]:
-Equation of state

$$p = \rho R T \tag{3}$$

-Continuity

$$\rho u A = cost \tag{4}$$

-Momentum

$$\rho u \frac{du}{dx} + \frac{dp}{dx} + JB = 0 \tag{5}$$

-Energy

$$\rho u \frac{d}{dx}\left(\frac{u^2}{2} + h\right) + JE = 0 \tag{6}$$

-Modified Ohm's law

$$J = (1 - K)\sigma u B \tag{7}$$

In the above equations ρ is the plasma density (kg/m^3), R (kJ/kg K) the gas constant, u the plasma velocity (m/s), A (m^2) the cross section of the duct, J the current density (A/m^2), B the magnetic field (T), h the enthalpy per unit mass (kJ/kg), E (V/m) the electric field ($E=uB$), σ the scalar conductivity of the plasma (1/ohm m), K the electrical loading factor, defined as the fraction of the total power generated that is actually extracted.

Moreover, since the electrical conductivity and magnetic Reynolds number is small for practical MHD generators, the effect of the generated currents on the applied magnetic field are ignored and hence the applied magnetic field is assumed to be constant.

The electric power extracted results:

$$P_{MHD} = JEV \tag{8}$$

where V is the volume of MHD duct.

For a given initial flow field, electrical loading factor, electrical conductivity and magnetic field, a spatially varying current is computed using the equation (7). Knowing the spatial distribution of current, the Lorentz force in the momentum equation and the work done by Lorentz forces needed in the energy equation is also evaluated. Having computed the MHD related source terms in the momentum and energy equations, an inviscid compressible flow solver is used to obtain converged solution of the velocity field. Based on the velocity distribution computed using the flow solver, the total power generation is calculated using eq.(8).

The rightness of the modeling assumptions and the validation of the MHD generator model have been carried out by using experimental and numerical data available from scientific literature [5,15,16].

4. Results and discussion

In the MHD duct calculation the plasma velocity u is assumed constant, while the conductivity has been estimated as the average between the initial and final values, according with experimental data available in the scientific literature for combustion gases seeded with potassium carbonate [5].

In table 2 the operating parameters of the MHD generator are summarized.

Table 2. MHD operating parameters

Combustion Chamber	
Fuel input (MW_{HHV})	27.13
$P_{CC,out}$ (bar)/ $T_{CC,out}$ (°C)	5/2725
Nozzle	
Mach number, M	0.8
MHD duct	
Magnetic Field density flux (T), B	3
Loading factor, K	0.5

In order to define the operating conditions for an efficient recovery of the thermal energy available from the MHD exhausts a sensitivity analysis has been carried out by varying the preheating temperature of air (or enriched air) sent to the combustion chamber.

4.1. CF-MHCC system performance

As previously discussed, the air preheating temperature is set at a fixed value of 800°C, in order to avoid the slag condensation and solidification. This means that the integration between the MHD generator and the steam power plant (the bottoming cycle) is rigid. Since the oxidizer temperature and the recirculated heat are not sufficient to obtain combustion plasmas of about 3000 K, oxygen enrichment is necessary. Thus, the air combustion is enriched with oxygen provided by the ASU (it is a stand-alone unit operating at 19 bar and generating pure 95% oxygen at a pressure of 6.25 bar).

The steam power unit is a two pressure level system and its operating parameters such as maximum pressure and turbine inlet temperature have been chosen in accordance with data usually adopted for bottoming cycles of conventional combined power plants. The polytropic efficiencies of compressors and turbines have been assumed equal to 0.9.

Table 3 reports the main working conditions resulting from the thermodynamic analysis and the energy balance of the CF-MHCC plant.

Table 3. Working conditions and Power Balance of CF-MHCC

MHD generator		
MHD exhausts mass flow	kg/s	10.01
Air enrichment	% O_2	24
$T_{nozzle,out}$/ $p_{nozzle,out}$	°C/ bar	2515/3.41
u	m/s	794
$T_{MHDduct,out}$/ $p_{MHDduct,out}$	°C/ bar	2104/0.65
$T_{diff,out}$ /$p_{diff,out}$	°C/ bar	2341/1.08
$P_{MHD,specific}$	MW/m^3	16.9
average conductivity	1/ohm m	11.92
Interaction Lenght	m	6.5
Steam Power Plant		
HP/LP pressure	bar	100/35
HP/LP temperature	°C	550/500
HP/LP steam production	kg/s	5.8/1.2
condensation pressure	bar	0.05
Power Balance		
P_{MHD}	MW	7.85
P_{SPU}	MW	8.63
P_{GROSS}	MW	16.5
$P_{air,CC}$	MW	-1.51
P_{ASU}	MW	-0.67
P_{COMP}	MW	-2.18
P_{NET}	MW	14.3
system efficiency (HHV), η_{SYS}	%	52.8

The system efficiency has been calculated as:

$$\eta_{SYS} = \frac{P_{NET}}{\dot{m}_{Coal} HHV} \tag{9}$$

where P_{NET} is the net electrical power generated.

Due to the very high temperature differences between the MHD exhausts and the feed water/steam (the feed water is heated to only 550°C), the heat recovery at high temperature is not optimal, involving great exergy losses. Moreover, the air separation power consumption for oxygen production is also a critical factor in upgrading the total efficiency performance of the coal-fired MHD system that is equal to 52.8%.

4.2. *IG-MHCC system performance*

The gasification pressure and temperature are assumed equal to 30 bar and 1300°C respectively. In order to increase the coal conversion the steam to carbon ratio S/C (defined as the ratio between the mass flow rate of steam and that of input coal) has been set to 0.7. In this condition the molar fractions of H_2 and CO, on dry basis, are 48% and 41% [1]. In order to reach the temperature required by the hot gas cleanup unit, the syngas is cooled in HEX (see Figs 2 and 3) by generating the steam for gasification reactions up to 500°C, and expanded close to the operating pressure of the MHD combustion chamber.

The air preheating temperature ranges from 1000°C to 1800°C, so the heat recirculated to the combustion chamber varies between 13% to 45% of the thermal energy available from the MHD exhausts. The main working conditions resulting from the thermodynamic analysis and the energy balance of the IG-MHCC,A plant configuration are summarized in table 4.

Table 4. Working conditions and Power Balance of IG-MHCC,A

Tair	°C	1000	1200	1400	1600	1800
MHD Generator						
MHD exhausts mass flow	kg/s	7.05	7.58	8.50	9.64	11.08
Air enrichment	% O_2	31	28	23	21	21
$T_{nozzle,out}$/ $p_{nozzle,out}$	°C	2541/3.44	2538/3.44	2532/3.43	2526/3.43	2521/3.42
u	m/s	783	785	789	791	793
$T_{MHD,duct,out}$/ $p_{MHD,duct,out}$	°C/bar	2167/0.65	2158/0.65	2145/0.65	2132/0.65	2119/0.65
$T_{diff,out}$/ $p_{diff,out}$	°C/bar	2378/1.05	2374/1.06	2369/1.07	2364/1.08	2358/1.08
$P_{MHD,specific}$	MW/m^3	16.4	16.5	16.6	16.8	16.9
average conductivity	$ohm^{-1}m^{-1}$	11.9	11.9	11.9	11.9	11.9
Interaction Lenght	m	6.7	6.6	6.6	6.5	6.5
Steam Power Plant						
HP/LP pressure	bar	100/35	100/35	100/35	100/35	100/35
HP/LP temperature	°C	550/500	550/500	550/500	550/500	550/500
HP/LP steam generation	kg/s	4.6/1	4.4/1.2	4.2/1.3	4.0/1.4	3.6/1.6
condensation pressure	bar	0.05	0.05	0.05	0.05	0.05
Power Balance						
P_{MHD}	MW	6.29	6.77	7.58	8.58	9.82
P_{SPU}	MW	6.42	6.32	6.21	6.11	5.94
$P_{EXPANDER}$	MW	1.59	1.59	1.59	1.59	1.59
P_{GROSS}	MW	14.3	14.7	15.4	16.3	17.3
$P_{air,CC}$	MW	-0.74	-0.88	-1.13	-1.39	-1.68
P_{ASU}	MW	-2.67	-2.42	-1.91	-1.66	-1.66
P_{OX}	MW	-0.20	-0.20	-0.20	-0.20	-0.20
P_{COMP}	MW	-3.61	-3.5	-3.23	-3.24	-3.53
P_{NET}	MW	10.7	11.2	12.1	13.0	13.8
system efficiency (HHV), η_{SYS}	%	39.4	41.2	44.8	48.1	51.0

The heat recirculation has different effects on electric power consumption and generation (P_{COMP} and P_{GROSS}). In fact, at lower air preheating temperature (less than 1500°C) it is difficult to attain the combustion temperature needed for plasma generation, so that air enrichment is necessary (from 31% to 23%). This involves a higher power consumption of the ASU (it provides the oxygen for gasification and that for syngas combustion) even if a lower amount of combustion air is required (the power consumption $P_{air,CC}$ of the related compressor is smaller). The power generated by the MHD generator increases with the air preheating temperature due to the greater plasma mass flow moving across the system.

Moreover the power produced in the steam power plant decreases slightly with the increasing in the air combustion temperature because the input thermal power available is almost constant (the reduction of thermal gradient is covered by the greater mass flow rates of the MHD exhausts). The system efficiency ranges from 39.4% to 51% meaning that at higher air preheating temperature a better heat recovery is realized.With respect to the CF-MHCC plant the efficiency penalty of IG-MHCC,A is very low resulting less than 2%.

An improvement of system efficiency is expected by considering the IG-MHCC,B plant configuration in which a high temperature heat recovery level has been introduced. The CGTC is an intercooled and regenerative cycle operating with nitrogen (CO_2 could be also considered if its capture and sequestration is performed). The operating parameters and the performance of the IG-MHCC,B plant are reported in table 5 (the performance and the working conditions of the topping cycle, the MHD generator, are not listed because they are the same of the IG-MHCC,A).

The turbine inlet temperature (TIT) is assumed equal to 1500°C, as in the advanced gas turbines commercially available, for air preheating temperatures equal or less than 1600°C, while a TIT of 1350°C has been chosen for T_{air}=1800°C due to the lower temperature of MHD exhausts from the HTHE.

Results show that the system efficiencies are enhanced in the whole air preheating temperature range, achieving a maximum value of 60%.

Table 5. Working conditions and Power Balance of IG-MHCC,B

T_{Air}	°C	1000	1200	1400	1600	1800
Closed Gas Turbine Cycle						
N_2 mass flow	kg/s	11.5	11.5	11.5	11.5	12
compression ratio, β	-	20	20	20	20	20
TIT	°C	1500	1500	1500	1500	1350
Pth,in	MW	13.2	13.3	13.3	13.3	12.6
Steam Power Plant						
HP/LP pressure	bar	100/35	100/35	100/35	100/35	100/35
HP/LP temperature	°C	550/500	550/500	550/500	550/500	550/500
HP/LP steam generation	kg/s	1.2/0.65	1.2/0.5	1.2/0.37	1.2/0.24	1.2/0.39
condensation pressure	bar	0.05	0.05	0.05	0.05	0.05
Power Balance						
P_{MHD}	MW	6.29	6.77	7.58	8.58	9.82
P_{SPU} +P_{CGTC}	MW	9.5	9.35	9.21	9.07	8.4
$P_{EXPANDER}$	MW	1.59	1.59	1.59	1.59	1.59
P_{GROSS}	MW	17.4	17.7	18.4	19.3	19.8
$P_{air,CC}$	MW	-0.74	-0.88	-1.13	-1.39	-1.68
P_{ASU}	MW	-2.67	-2.42	-1.91	-1.66	-1.66
P_{OX}	MW	-0.20	-0.20	-0.20	-0.20	-0.20
P_{COMP}	MW	-3.61	-3.5	-3.23	-3.24	-3.53
P_{NET}	MW	13.8	14.2	15.1	16.0	16.3
system efficiency (HHV), η_{SYS}	%	50.7	52.4	55.8	59.0	60.0

5. Conclusion

The aim of this paper was to investigate the performance of different plant configurations based on open-cycle MHD generators fed with coal (CF-MHCC) and syngas produced by coal gasification (IG-MHCC,A and IG-MHCC,B). Therefore, the CF-MHCC is a conventional configuration in which the plasma gas is the products of direct combustion of coal, while the IG-MHCC,A and IG-MHCC,B configurations can be considered as advanced type because the working fluid is the products of syngas combustion.

The power plants analysis has been performed by developing an integrated model between the thermochemical and thermodynamic models required to characterize mass and energy balances of each system component and the electro-magnetic equations needed to solve the energy balance in the MHD generator.

Results show that the heat recirculation to the combustion chamber (the thermal energy transferred to the air combustion by the cooling of MHD exhausts) has a significant impact on system efficiency.

In the CF-MHCC plant the air preheating temperature is fixed to 800°C to avoid slag condensation, so the heat recovery at high temperature is not optimal and the system efficiency, referred to the HHV of input coal, is only of 52.8%.

In the IG-MHCC,A plant, the air preheating temperature ranges from 1000°C to 1800°C because no slag is involved, so the heat recirculated to the combustion chamber varies between 13% to 45% of the thermal energy available from the MHD exhausts. The system efficiency ranges from 39.4% to 51% meaning that at higher air preheating temperature a better heat recovery is performed. With respect to the CF-MHCC plant the efficiency penalty is very low resulting less than 2%.

In order to improve the system efficiency a high temperature heat recovery level has been introduced in the plant configuration by using a closed gas turbine cycle (IG-MHCC,B). Results show that the system efficiencies are enhanced, achieving a maximum value of 60%. This means that higher system efficiencies could be further obtained by optimizing the working conditions of topping (the MHD generator) and bottoming cycles (the CGTC and SPU).

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