HAL
open science

A new electro-burner concept for biomass and waste combustion

Laurent Fulcheri, Vandad-Julien Rohani, Sabri Takali, Frédéric Fabry, François Cauneau

To cite this version:

Laurent Fulcheri, Vandad-Julien Rohani, Sabri Takali, Frédéric Fabry, François Cauneau. A new electro-burner concept for biomass and waste combustion. 6th International Conférence on Engineering for Waste and Biomass valorisation - WasteEng2016, May 2016, Albi, France. hal-01328475

HAL Id: hal-01328475

https://minesparis-psl.hal.science/hal-01328475v1

Submitted on 9 Jun 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A new electro-burner concept for biomass and waste combustion

Laurent Fulcheri*, Vandad Rohani, Sabri Takali, Frédéric Fabry, François Cauneau

MINES ParisTech, PSL Research University, PERSEE - Centre procédés, énergies renouvelables et systèmes énergétiques, CS 10207 rue Claude Daunesse 06904 Sophia Antipolis Cedex, France

*Laurent.fulcheri@mines-paristech.fr

Keywords: Biomass/Waste, Combustion, Plasma, Electro-burner

Abstract

Raw biomass resources and many wastes are composed of poor-LHV organic matter (LHV < 20 MJ/kg). Their use as renewable fuels for heat or power generation is challenging, particularly when they are in solid form. Indeed, their combustion in air is critical and it is not possible to build autonomous burners independently of external conditions without an assistance. Three main options are currently studied: (i) the co-combustion, in which the poor-LHV fuel flame is supported thanks to an additional rich fuel, (ii) the oxy-combustion (iii) the electro-combustion, consisting in the generation of thermal plasma for activating and assisting the combustion. This last option is highly interesting because it only requires electricity (having low carbon content if renewable electricity). Depending on the nature of the feedstock, the electric power of the plasma does not exceed 1% to 5% of the flame power. Most plasma electro-burners technologies today on the market use DC plasma torches. These technologies suffer from many drawbacks among which: limited electrodes lifetime, poor reliability, important water cooling needs, need of AC/DC transformers, etc. leading to high CAPEX and OPEX. With the objective to go over these limits and reduce OPEX and CAPEX while increasing reliability, the Center PERSEE MINES-ParisTech has been working in the development of an original three-phase AC plasma technology to be integrated in a plasma electro-burner. This paper presents the main achievements on the plasma technology with a special focus on the limitation of electrodes erosion thanks to an active thermo-chemical gas sheathing.

1- INTRODUCTION

In the present context of conventional fossil fuel depletion and global warming, energy production from biomass and organic wastes is a major challenge for the future of society and environment. Most of crude renewable organic resources are characterized by a low heating value and their direct combustion in air can only be achieved in a high temperature environment. Due to the increase of renewables in the energy mix, together with fluctuation of electricity demand, modern thermal power plants using low heating value feedstock are more and more led to operate under dynamic conditions including low temperature operation conditions during start up, heat up and low load phases. To face these evolutions in operation modes, the most developed technique consists in using assistance to combustion thanks to specific additional burners working with rich fossil fossils, generally natural gas or heavy fuel. This solution is constraining, costly and environmentally damaging since it not only implies the combustion of expensive rich fossil fuels but also increased operating cost due to additional burners and side elements.

For few years, new alternative solutions for the assistance of low heating value feedstock combustion have emerged. Among these news techniques, the plasma assistance combustion

is particularly promising and attractive. The principle is based on the controlled thermochemical activation of the combustion thanks to the use of plasma whose power generally does not exceed few percent of the combustion thermal power. Such systems, called plasma electro-burners present number of advantages versus traditional technologies based on partial oxidation or combustion among which: their ability to deliver and tune the enthalpy and/or temperature through an external energy supply with temperatures that cannot be achieved with combustion methods, their very short dynamic response, their limited environmental impact (no direct CO2 emissions), their flexibility and ability to operate under very different atmospheres (neutral, reducing or oxidant), and their compactness due to their very high volumetric energy density which opens the way to process intensification.
Most plasma electro-burners technologies today on the market use DC plasma torches. These technologies suffer from a certain number of weaknesses and drawbacks among which: limited electrodes lifetime, poor/limited reliability, important water cooling needs, need of AC/DC transformers leading to high Capital (CAPEX) and Operational (OPEX) costs.
With the objective to go over these limits and reduce OPEX and CAPEX costs while increasing reliability, the Center PERSEE MINES-ParisTech has been working for many years in the development of an original 3-phase AC plasma technology to be integrated in a plasma electro-burner.

2- BIOMASS AND WASTE

In 2050, primary energy consumption would reach 22.6 Gtep i.e. three fold the 2000 consumption (7.38 Gtep). Simultaneously the share of electricity would rise from 34 % to 42.5 %. According to B1-GIEC and IMACLIM-CIRED scenarii, the share of biomass in the energy mix would reach in 2050 a part comprised between 9.7 % and 14.4 % (2.2 to 3.25 Gtep). In conventional thermal power plants where coal plays today a major role, the decrease of coal share to face up to critical environmental issues will necessarily involve an increase use of biomass and wastes. Indeed, as shown on Table 1, the economic and environmental advantages of this renewable resource are obvious: (i) a highly competitive MWh price versus other renewable energy technologies (wind, hydro or solar) and fossil fuels, (ii) an expected CAPEX (2030) among the lowest on the market and (iii) greenhouse gases emissions around 30 kg CO2 equivalent per MWh corresponding to 10 % of fossil fuel emissions and same order of magnitude than other renewable energy technologies.
Biomass can be considered as a form of solar energy storage during the photosynthesis process. It is often considered as a clean energy. However, In many cases, non-sustainable biomass resource exploitation can create important environmental damages and it is important to keep in mind that biomass can be considered as a clean and renewable energy resource only on condition that it is accompanied by a sustainable policy. Biomass can have different origins (agricultural, farming or food industry residues, sewage sludge, municipal wastes, dedicated energy plantations…) and it can be classified into three main categories depending on its state: gas, liquid or solid. With 10 Mtep in 2011, France is the first European country in terms of wood exploitation [2]. We will focus in the following on solid biomass only.

3- SOLID BIOMASS FOR ENERGY PRODUCTION

Solid biomass can be used for electricity production and its use in thermal power plant is increasing since the resource is more abundant than biogas and biofuels. Most developed countries engaged towards a clean energy transition policy follow this strategy with the aim to “decarbonize” their energy but also to limit their fossil fuel dependency.

In France, solid biomass resource for electricity production per year (residues from forest industry and wood transformation industry, straw…) is estimated to 5 Mtep plus 0.5 Mtep of sewage sludge (potential of non-exploited resource). Most of this biomass is characterized by LHV (Low Heating Value) varying between 6 to 20 MJ/kg, Chlorine and Sulphur contents generally lower than 0.1 % and very high water content generally ranging from 30 to 50 % of the mass, hence the need for drying it before they use for energy purposes [3].
We give on Table 1 the typical characteristics of biomass feedstock used in a Polish thermal power plan (Poloniec) for the co-combustion with coal.

	Mixure (80 % wood 20 % agro)	Wood ships	Agro	Straw-pellets	Sun flower	Palm nut shell
			Raw Biomass			
Humidy (%)	35,90	42,40	11,55	13,00	11,50	9,70
Ash content (%)	1,80	0,29	2,63	-	2,90	2,00
LHV ($MJ.kg^{-1}$)	10,50	9,40	15,85	14,80	16,00	17,90
Density ($kg.m^{-3}$)	350	300	437,5	600	600	300
			Wet Biomass			
Volatile (%)	--	80,00	80,78	83,10	80,00	80,00
Ash (%)	2,81	0,50	3,95	6,90	3,28	2,20
C (%)	49,15	49,75	49,01	45,83	49,51	53,69
H (%)	5,96	6,12	5,86		5,91	5,80
N (%)	0,25	0,05	0,87	0,80	0,93	0,49
O (%)	--	43,50	40,25	40,63	40,21	37,78
S (%)	0,05	0,04	0,11	0,15	0,16	0,04
Cl ($mg.kg^{-1}$)	--	100	550	1 000	700	300
P ($mg.kg^{-1}$)	--	100	1 150	1 000	1 600	300
alkalin (Na+K) acid soluble ($mg.kg^{-1}$)	--	600	6 650	10 000	11 000	1 300

Table 1: Characteristics of biomass used in the Polish Poloniec power plant (mass fractions) for co-firing with coal.

China which is the country having highest energy consumption and CO2 emissions is currently massively investing on biomass integration technologies in the energy mix. In 2010, 5.5 GW electricity production from biomass was achieved among which 62% was directly produced by wood-energy [4]. The objective for 2020 is to reach 30 GW; this will need a USD$ 3.1 billion investment. Today the number of thermal power plants in China using biomass is estimated between 500 and 700 [4]. In order to support this policy, a $USD 0.039 subsidized price for electricity production from biomass is currently applied.
Thermal processes for large scale energy production from biomass can be classified into three main categories: **pyrolysis, gasification and combustion.** This later is the most common since it accounts around 97% in the global bioenergy production.
The high water content is generally a major drawback for biomass combustion and sustaining a continuous and stable flame need humidity content lower than 65 % [5]. Fixed and fluidized beds are the most developed technologies for solid biomass combustion [6]. Fixed bed being far away the most simple and spread option for small units while fluidized bed technologies allow achieving higher yields are most suitable for big installations.

The self-sustained and clean **combustion** of low heating value feedstock such as biomass is not obvious and is today an important scientific and technical challenge. The main drawback is that the combustion of low heating value feedstock in air can only be realized at high temperature which makes it highly dependent on the furnace thermal conditions. At low temperature, such as encountered during start up, heat up and low load regimes feedstock having a low heating value cannot be used without this add of an external energy source.
In order to exceed these drawbacks, three options for the combustion assistance of low heating value feedstock are today under development: (i) oxy-combustion, (ii) co-combustion (or co-firing) and (ii) plasma-assisted combustion.
In **oxy-combustion**, pure oxygen, generally produced by cryogenic processing with purity higher than 95%, is used as combustive. This allows obtaining a stable flame while limiting NOx production. The flue gases being mainly composed of CO2 and Steam this possibly opens the way towards the direct capture of CO2 in post combustion. The main drawback of this technique relies on the high cost of oxygen production which is around 0.20 - 0.22 kWh per kg of oxygen (cryogenic separation) [7].
As example, a technical and economical assessment of a 460 MW oxy-combustion coal power plant gives a cost comprised between 72 and 83 MW for the production of oxygen corresponding around 15-18 % of the total electric power [8]. In addition with increased operational costs (OPEX), investment costs (CAPEX) for an oxy-fuel combustion power plant is also high: 2 089 €/kW against 1 323 €/kW for a supercritical coal power plant [8].
The principle of **co-combustion** consists in using an extra fuel, generally fuel oil or natural gas to assist the combustion of a low heating value feedstock. It is today the most developed method used during the startup and heat up phases.

4- PLASMA ASSISTED COMBUSTION

Plasma, which represents about 99% of the universe, is often presented as the forth state of matter. It is composed of electrons, ions, molecules at fundamental or exited state. Thanks to existence of charge carriers (electrons and ions), plasmas are characterized by a high electric conductivity. Plasma systems can be classified into two main categories: non thermal plasma where temperature (energy) of heavy particles (molecules and ions) is much lower than those of electrons and thermal plasmas where all the species have approximately the same temperature (energy). In an environment having a low carbon content electricity, such as what can be expected in the future with a large scale development of renewable energy (wind, solar, …), plasmas are particularly attractive and may open the way towards breakdown technologies and solutions able to answer to major tomorrow' energy and environment challenges. Indeed plasmas allow: (i) an energy input without direct CO2 emissions which is: robust, flexible, instantaneous reactive and tunable in a very wide range of operating conditions (atmosphere, pressure…) and likely to lead to temperatures that may exceed temperatures encountered in conventional combustion processes, (ii) to increase efficiency and reduce environmental impacts of a wide range of industrial processes thanks to their ability to generate unique and very reactive chemical species.
As shown on Figure 1, plasmas can interact with combustion by different means [9] dealing with thermal, chemical and transport phenomena. On the thermal side, plasmas allow to increase the temperature and speed up the chemical reactions, including oxidation according to Arrhenius law. On the chemical side, plasmas can produce many active radical and species such as for example O, OH and H that have been identified as playing a major role in the chain combustion / oxidation mechanisms. On the transport side, generally considered as an indirect effect, plasma can participate to the breaking of big fuel molecules thus modifying the

combustion kinetics. Other effects linked with electromagnetic forces acting of a source of momentum can have a great impact on the fluid dynamics and heat and mass transfer.

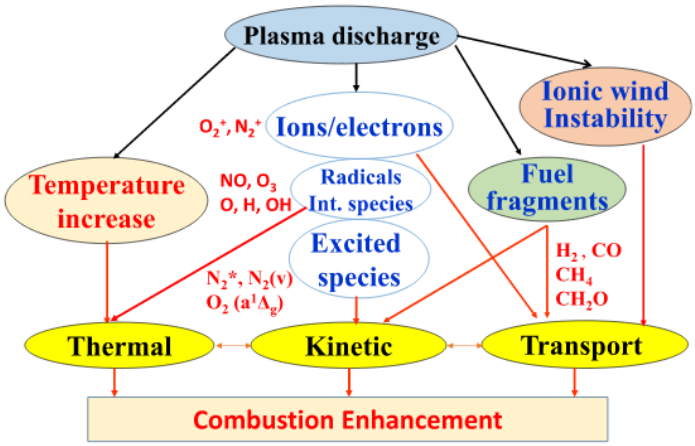


Figure 1: Role of plasma in combustion enhancement [9].

Plasma assisted combustion presents a great potential in many industrial sectors such as internal combustion engines [10-12], turbo machines and gas turbines [13-14] and thermal power plants [15]. Spark ignition of internal combustion engines, plane reactors or gas turbines is the most common "plasma system". In a standard spark plug, an electrical breakdown is created between two electrodes allowing ionizing and cracking molecules of the mixture air-fuel. This ignites the combustion mechanisms locally and the flame can propagate towards the overall mixture. On this area, new advanced ignition technologies are currently under development by most engine, and turbo machines manufacturers.

5- PLASMA ELECTRO-BURNERS FOR COAL COMBUSTION

Plasma electro-burners can generate a stable flame with a low heating value feedstock even in a low temperature environment thanks to the thermo-chemical plasma activation. For economic and environmental reasons, this technology has today an exponential development in China in coal power plants in replacement of traditional burner (Figure 2).

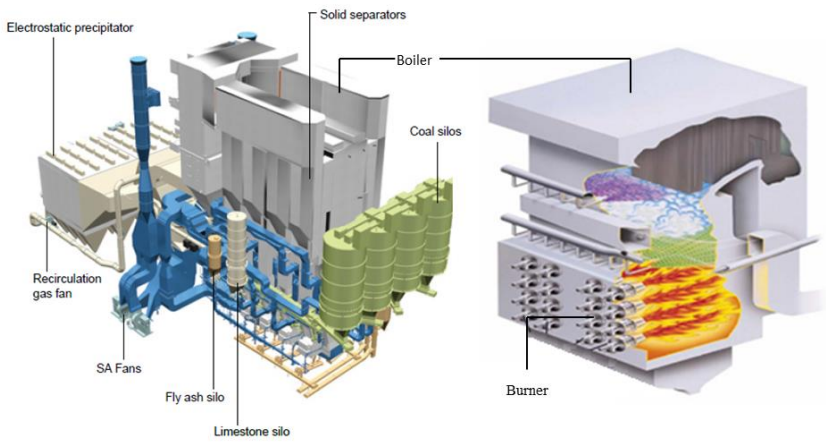


Figure 2: Scheme of a pulverized coal power plant: overall (left) and boiler (right).

80 % of new coal power plants installed in China are equipped with plasma burners: in October 2012 more than 627 boilers equipped with plasma burners were in operation in China corresponding to a total installed capacity around 265 GW (total power plants). Plasma technologies cover boiler with powers ranging from 50 to 1000 MW. The yearly savings of auxiliary fossil fuels was estimated to 5 million tons equivalent to 3.5 billion euros. Figure 3 shows a picture of the Tianjin Guodian coal power plant (China) equipped with plasma burners.

Figure 3: Tianjin Guodian coal power plant (China).

Most installations use classical DC plasma technologies with tungsten based cathodes. The main technology supplier is Yantai Longyuan Electric Power Technology Co. Ltd (Longyuan Corp.) with a market share around 95%. Longyuan was created in 1996; it became a China Guodian Corporation subsidiary in 1998. Longyuan first succeeded in implementing this technology in a 50 MW "Yantai Power Plant" in February 2000. In October 2007, this technology was successfully implemented in a 560 MW unit "Korea Samchonpo Power Plant". Despite the rapid growth of this new technology in China, it is likely this technology suffers from important weaknesses and drawback slowing down its development on the occidental market due to domestic standards issues [16]. In [17] one can find a representation of one patent filled by Yantai Longyuan Technology Co. Ltd in 2002.

In Eastern Europe, intensive researches have been carried by V. E. Messerle, A.B. Ustemenko and E. I. Karpenko group [18]. They developed a DC plasma technology. The nominal power of a single plasma torch is in the range 100 - 200 kW. This technology was implemented in 27 pulverized coal furnaces spread in 16 power plants located in 6 countries (Russia, Kazakhstan, Korea, Slovenia, Mongolia and China) [19]. Other studies have been carried out in Russia and Ukraine using a plasma micro wave technology but, tour knowledge this technology never reached the industrial stage [20]. Finally researches are currently carried out in Czech Republic and Poland by the company ORGREZ based on DC plasma technologies with power ranging from 20 to 100 kW [21].

In France, researches in the field have been carried out in 1984 by BERTIN and Cie. These researches led to a patent [22]. The reactor has two stages respectively upstream and downstream the plasma zone. The injection of fuel as plasma gas aims at reducing the electrode erosion. The plasma chamber is equipped with a convergent nozzle in the upstream area and a divergent nozzle in the downstream area.

In 1994, a patent was filled by the French utility EDF [23]. The system had several tangential air injection ports to create a vortex in the plasma gas and was working in DC.

6- CONCEPT OF PLASMA ELECTRO-BURNER FOR BIOMASS/WASTE COMBUSTION

With the recent necessity to limit the atmospheric CO2 concentration, Europe progressively turns away from coal and wish to replace it by regenerative solid biomass, including organic wastes. A lot of industrial sectors are concerned by this transition, going from energy sector to metallurgy, cement work, etc. Nevertheless, this change is not so trivial at technological level because the difference between these two fuel types can be significant (LHV, dryness, particle size and variability of the quality). Burners are within the first devices concerned by this change. In 80/90's, several plasma electro-burners were invented and developed for pulverized coal combustion in order to offer by means of a low electricity consumption (P_{elec} = few % of P_{comb}) the possibility for the plants to operate with one unique fuel while increasing the operation flexibility (see previous section). By the way, the current Chinese plasma electro-burners presented previously derived from them. This new category of burners has been somewhat put aside in Europe because of the slowing down of the European coal technology development. Today, with the drive to develop biomass sector, there is a resurgence of interest. But, a plasma electro-burner designed for coal combustion cannot be directly used for combustion of common biomass. It requires revisions: (i) minor ones, if adequate associated technologies of biomass pre-treatment (ultra-drying, roasting, pyrolysis) and injection (grinding and pulverization) are specially developed and set-up in order to upgrade the fuel and get comparable properties as coal, or (ii) major revisions, even complete redesign, if the goal would be to directly used weakly treated or raw biomass.

In any case, the technological challenges are significant, and the best solution would certainly need, at the same time, development efforts on the fuel pre-treatment processes and/or the injection technology, and on the plasma electro-burner technology itself.

The existing coal plasma electro-burners require a particle size of 50-100 μm [24]. The bio-materials able to be convenient and grinded at this size could be dried non-filamentous ones such as wood-char, dried sewage sludge, roasted kernel, bone meal and dried leaf. So, a special technology for grinding and pulverizing at a micron-size these materials must be designed.

On the burner side, it is important to note that the existing coal plasma electro-burners suffer from a lack of robustness due essentially to the plasma torch technology used inside them. The severe electrodes erosion coming from the combination of oxidative conditions and particles impact reduces drastically the life–time of the burners. Thus, whatever the fuel to be used, a consequent development effort must be done on the plasma torch technology before a large industrial deployment.

Despite the technological challenges, a biomass plasma electro-burner technology (Figure 4) would offer evident advantages. A robust tunable device allowing generating from biomass pulverized in air and low electricity consumption a stable flame independently of external thermal conditions would be a great advance for many sectors. Obviously, the quality of the combustion offered by the burner would be determinant for targeting its applications. For example, glass work sector is more demanding than energy sector on the quality of exhaust gases.

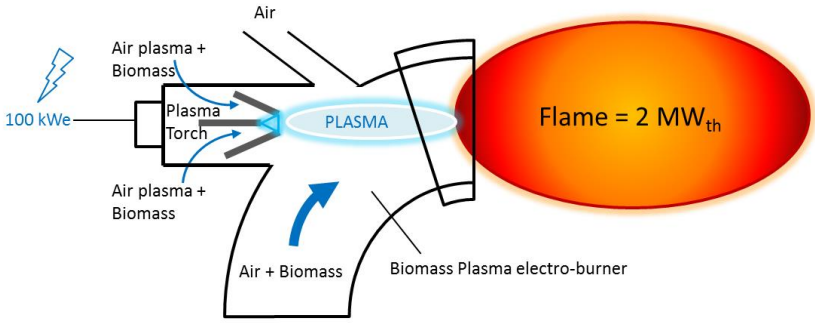


Figure 4: Scheme of a biomass plasma electro-burner.

Overall, in addition to the flexibility gain brought, the use of such biomass burners would allow guaranteeing for the future thermal installations a total independence from fossil fuels and making huge economy of atmospheric CO2. Assuming in the near future, a systematic regeneration of the biomass and availability of free-carbon electricity (renewable energy deployment), a biomass burner would lead to avoid the consumption of several million tons of fossil fuels. As an example, a 100 MW_{th}/25 MW_e biomass power plant needs to use 325 tons of oil per year for ensuring its flexibility and consequently emits 1980 tons/year of CO2. The use of plasma electro-burners in this case would require only 180 MWh carbon-free electricity per year for avoiding this CO2 pollution.

7- THREE-PHASE AC PLASMA TECHNOLOGY

Arc plasma technologies can be split into two main categories: DC and AC plasma torches [25-26]. DC plasma torches usually have a tip cylindrical geometry with the tip, generally cathode, located at the upstream axis of a narrow cylindrical nozzle, generally anode. The plasma plume is characterized by a very high velocity (several hundred m/s) resulting from the combined effect of the narrow nozzle diameter and the severe thermal expansion of the plasma gas due to strong gas heating.

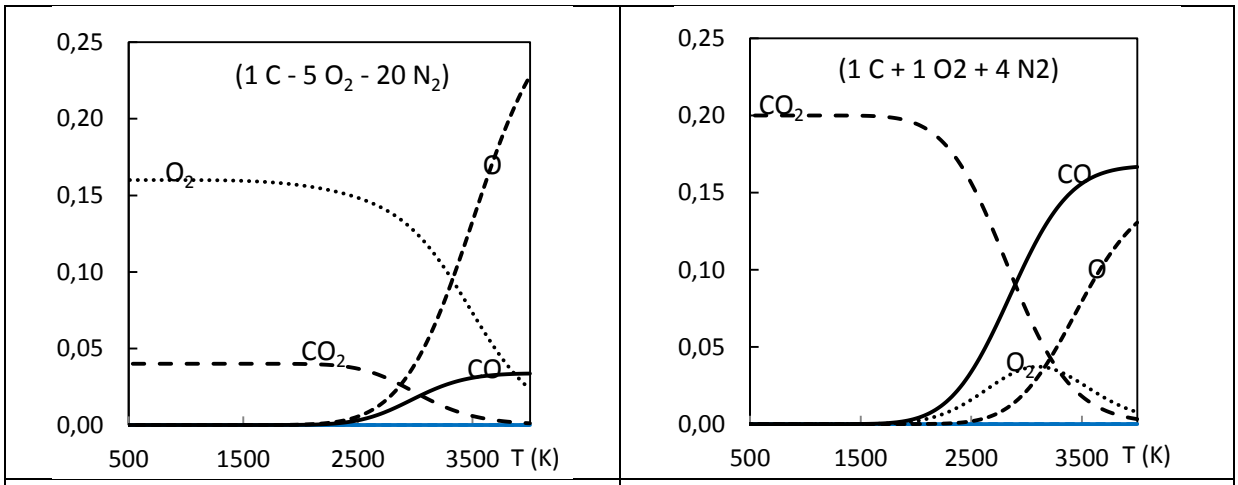
Despite continuous technological and material improvements DC plasma torches suffer from one critical weak spot: electrode erosion resulting in limited electrode lifetime due to the combination of very strong thermal, mechanical, and chemical constrains. Another drawback of DC plasma torches is the need for delicate and costly electronics for the AC–DC current rectifier which generally accounts about 30 % of the overall capital and operating costs.

On the other hand, AC plasma technologies have attractive features to exceed some of the critical drawbacks of DC plasma technologies [27]. In multiphase AC plasma systems, several arcs can coexist in a larger discharge chamber volume creating a large volume zone as the arcs are generally much less confined than in classical DC plasma torches. The plasma average temperature can consequently be significantly lower than in DC systems. With the plasma temperature decrease, radiation and convection heat losses can be strongly reduced, increasing the overall electro-thermal efficiency. Unlike DC, multiphase AC plasma systems can be supplied thanks to simple transformers, thus significantly reducing OPEX and CAPEX costs while increasing reliability and scalability. Each electrode acts successively as anode and cathode, leading to a more symmetrical operating mode than in DC systems and limited electrode erosion. The convection transfer within the plasma can be enhanced by the strong arc motion resulting from the self-induced MHD forces. Finally, AC plasma systems can use different electrode materials that can be water-cooled (copper, stainless steel, tungsten…) or consumable (graphite…).

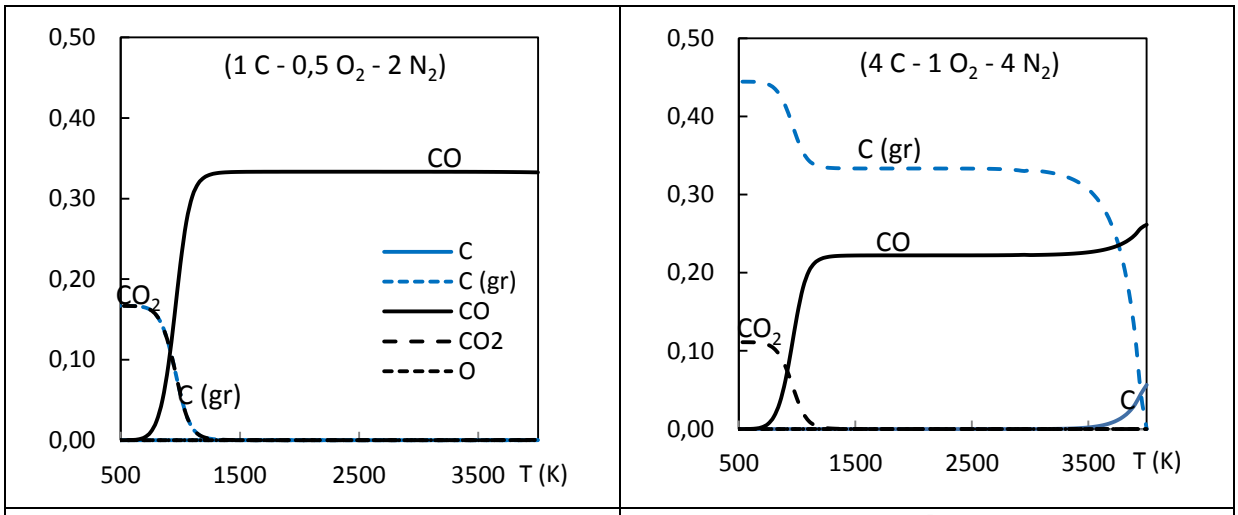
In 1973, at CNRS-Odeillo, France, Bonet started working on the development of a three-phase AC plasma technology for the high temperature treatment of refractory materials [28]. The research led to a very intense technological effort, and to the study and analysis of a wide range of prototypes and design options together with electrode materials and plasma gases. Between 1979 and 1980, the French Lafarge cement company in collaboration with the Limoges University and CNRS-Odeillo led a collaborative research program on raw cement powder decarbonization based on Odeillo's three-phase AC technology. The feasibility of the process was demonstrated but it was abandoned probably for economic reasons.
In 1986, the French engineering company Bertin in collaboration with the French utility company EDF worked on the development of a hybrid 500 kW electro-burner prototype [29-30]. The plasma technology was inspired from Odeillo's technology. Despite significant technological achievements, the concept never reached the industrial scale and was abandoned in the 1990s.
The development of the three-phase AC technology started again in 1993 in collaboration between PROMES-CNRS and PERSEE MINES-ParisTech in the field of hydrocarbon cracking for the co-synthesis of carbon black and hydrogen [31-34]. The R&D continued between 1997 and 2003 through three successive European projects. In parallel with the production of carbon black, it was demonstrated the three-phase AC plasma technology was also particularly suitable for the large scale synthesis of fullerenes and carbon nanotubes [35-36]. In 2002, the 250 kW three-phase AC plasma equipment, initially located at PROMES-CNRS Odeillo, was moved to PERSEE MINES-ParisTech Sophia Antipolis. Between 2004 and 2009, the development of the technology continued in collaboration between MINES-ParisTech and TIMCAL with the objective of bringing the technology at a pilot scale. Since 1993, four international patents have been granted, more than 30 papers were published in peer review journals [38-53] and four PhD theses carried out.
In his PhD, Fabry 1999 [37] focused on the development of experimental devices, diagnostic tools for the three-phase AC reactor, experimental analyses based on macroscopic heat and mass balances, as well as experimental plasma flow diagnostics.
Meanwhile, Ravary [38] demonstrated that the flow was highly influenced by the arc motion. The presence of three electrodes creates a mutual electromagnetic influence of the arcs which deeply modifies the. To analyze this complex behavior, a high-speed cinema camera was used to film the arc zone. Movies showed the importance of the electromagnetic forces applied on the arcs which consequently had very characteristics motions. On the theoretical side, the forces have been evaluated in a simplified geometry. This estimation proved to be in qualitatively good agreement with the phenomena. A simplified model derived from the electromagnetic force model was used as a source of momentum as input of the CFD model [39-40]. A comprehensive summary of achievements obtained between 1993 and 2003 is given in [41].
In his PhD, Rehmet 2013, [42] deepened the analysis of the three-phase AC plasma system on non-reactive conditions (nitrogen, syngas) through an original approach carried out in parallel on the theoretical and experimental sides. The experimental study was based on high speed video camera and electrical signal analyses. The theoretical analysis was made through the development of an unsteady 3D Magneto- Hydro-Dynamic (MHD) model using the CFD software Code_Saturne. A parametric study based on current, frequency, plasma gas flow rate and electrode configurations (coplanar and parallel), was carried out. These studies confirmed and highlighted the dominant influence of the electromagnetic phenomena. In a paper published in 2013, Rehmet [43] presented MHD numerical model. The experimental results published in a follow up paper [44-45] showed the arc behavior was totally in line with modeling results. Results showed that the electrode jets due to Maecker effect were playing an essential role. The influence of the electrode configuration was studied in [46]. In the coplanar

electrode configuration, the arcs remain confined within the inter-electrode gap and arc behavior is mostly controlled by electrode jets while, in the parallel electrode configuration, the arcs length increases. In this configuration, arcs are pushed toward the axial and radial directions by the combined effect of electrodes jets and Lorentz forces along the arc column. This work showed the plasma power could efficiently be controlled by artfully adjusting the electrodes layout.

At this time, the 3-phase AC plasma technology with graphite electrode was able to run under any neutral or reducing plasma gas (argon, helium, nitrogen, hydrogen, carbon monoxide, syngas,…) but hardly under oxidizing conditions (air, oxygen, carbon dioxide,…) due to strong electrodes erosion. This issue was addressed by Takali in 2015. In his PhD dissertation [47], Takali studied the development of a 100 kW plasma torch working in air to be embedded in an industrial electro-burner in making possible an operation in oxidizing environment by reducing as much as possible the air erosion of the graphite electrodes. For this purpose, different methods were imagined, investigated and tested on both theoretical (numerical modeling) and experimental sides. The by far best solution involved the injection of a carbonaceous element under finely controlled conditions acting as sheathing agent at the vicinity of the electrodes. The challenges lies in being able to control the oxidation to locally keep an atmosphere having a mixture closed to syngas (mixture CO-H2) which behaves neutral at high temperature with carbon (neither oxidant nor reducing). To illustrate this, Figure 5 represents the composition (molar fractions at thermodynamic equilibrium) of a mixture (C / O_2 / N_2) versus temperature for four increasing C/O2 ratios: 0.2, 1, 2 and 4 respectively. It appears clearly that cases (a) and (b) must be avoided since it would strongly erode graphite electrodes while cases (c) and (d) must be researched since it would not chemically interact with solid carbon.



(a) (b)



(c) (d)

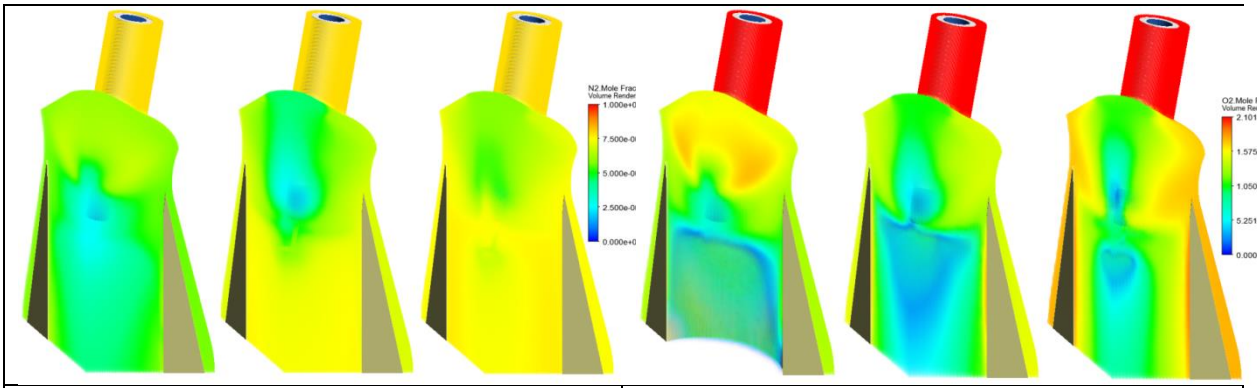
Figure 5: Composition (molar fractions at thermodynamic equilibrium) of a mixture (C / O_2 / N_2) versus temperature for four increasing C/O2 ratios: 0.2, 1, 2 and 4 respectively

Among the different cheap carbonaceous element likely to be used as electrodes sheathing, natural gas is particularly attractive. Indeed, its partial combustion in air would produce a mixture of carbon monoxide and hydrogen (syngas). In order to study this, a CFD numerical model based on the Jones-Lindstedt reduced kinetic model [48] has been developed in the fluent CFD code (« Laminar finite-rate » model).

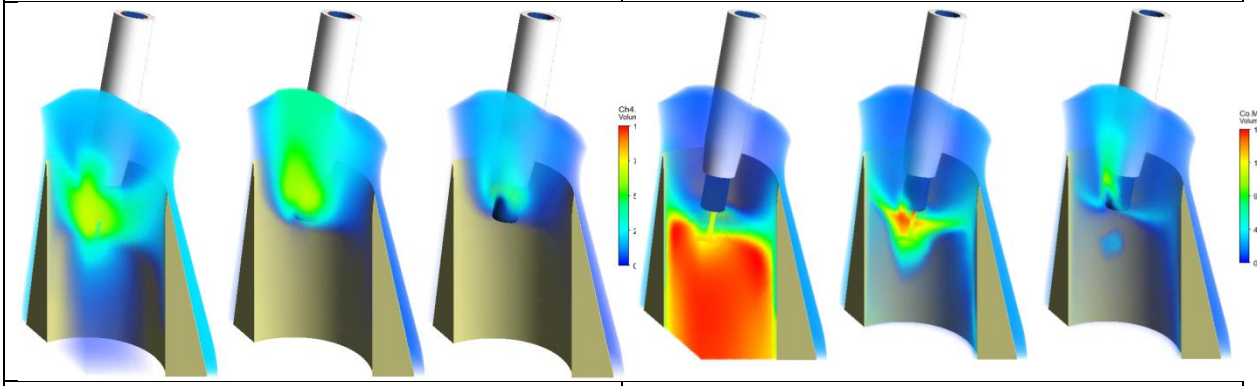
	Réactions	*A*	*b*	*E*	*υ*	Réf
II. 1_d	$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	$0{,}44\ 10^{12}$	0	$2{,}49\ 10^{8}$	$[CH_4]^{0,5}\ [O_2]^{1,25}$	[170]
II. 2_d	$CH_4 + H_2O \rightarrow CO + 3H_2$	$0{,}30\ 10^{9}$	0	$2{,}49\ 10^{8}$	$[CH_4]\ [H_2O]$	[170]
II. 3_d	$H_2 + 0.5\ O_2 \rightarrow H_2O$	$0{,}68\ 10^{16}$	-1	$3{,}32\ 10^{8}$	$[H_2]^{0,25}\ [O_2]^{1,5}$	[170]
II. 4_i	$H_2O \rightarrow H_2 + 0.5\ O_2$	$7{,}06\ 10^{17}$	0	$8{,}06\ 10^{9}$	$[H_2]^{-0,75}[O_2][H_2O]$	[172]
II. 5_d	$CO + H_2O \rightarrow CO_2 + H_2$	$0{,}27\ 10^{10}$	0	$1{,}66\ 10^{8}$	$[CO]\ [H_2O]$	[170]
II. 6_i	$CO_2 + H_2 \rightarrow CO + H_2O$	$6{,}71\ 10^{10}$	0	$1{,}14\ 10^{8}$	$[CO_2]\ [H_2]$	[173]

Table 2: Kinetics data for the Jones and Lindstedt mechanism.

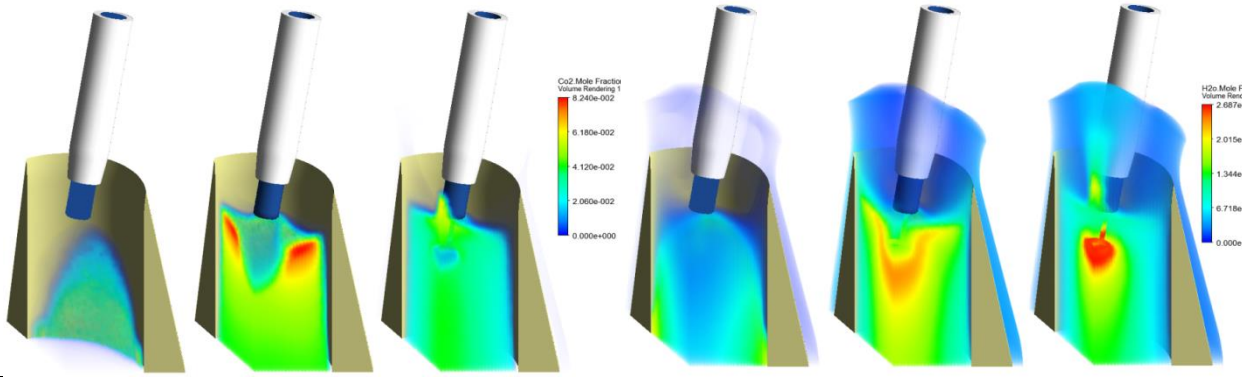
Methane is injected around the electrodes at three flow rates: 1.5 $Nm^3.h^{-1}$, 3 $Nm^3.h^{-1}$ and 6 $Nm^3.h^{-1}$ respectively. As shown on Figure 6, methane flow rate shows a huge influence on spatial distribution of the gas composition. At high methane flow rate, methane is blown toward the discharge zone and reaction with oxygen takes place below the electrodes. For this reason, the areas with high CO and H_2 concentrations are localised undernith the electrodes. When decreasing the methane flow rate from 6 $Nm^3.h^{-1}$ to 3 $Nm^3.h^{-1}$, CO and H_2 are produced along the transversal area of the électrode. In this case, as a result of the methane velocity decrease, the residence time at the vicinity of the electrodes is higher and in line with the kinetics of the partial oxidation. On the other hand, when reducing the methane flow rate to 1.5 $Nm^3.h^{-1}$, the methane velocity become too low to sheath electrodes and the CO and H_2 remains very low. Experiments confirmed the great interest of this solution together with the strong sensitivity of methane flow rate on the local concentration of CO and and H_2 and consequenly on the erosion rate of the electrodes. In our specific case, an optimal methane flow rate around 3 $Nm^3.h^{-1}$.. was found giving erosion rates as low as 0.1 to 0.01 g/kWh similar to erosion rates obtained with nitrogen.



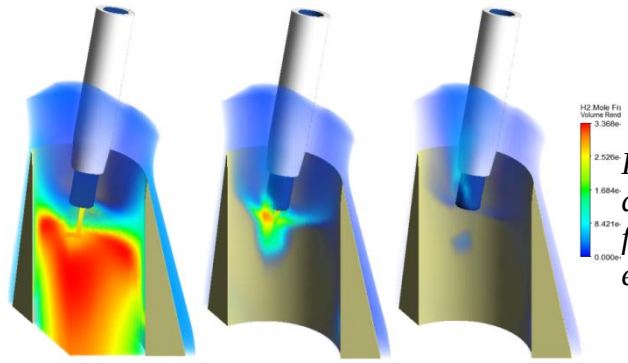
N2 mass fraction From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$	O2 mass fraction From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$



CH4 mass fraction From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$	CO mass fraction From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$



CO2 mass fraction From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$	H2O mass fraction From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$



H2 mass fraction
From left to righ Q_{CH4} = 6, 3 and 1.5 $Nm^3.h^{-1}$

Figure 6: Influence of methane flow rate on distribution of the gas component mass fractions. The air flow rate is here fixed and equal to 65 $Nm^3.h^{-1}$.

To finish, Figure 7 illustrates drawings of the three-phase AC plasma torch specially designed for being integrated at a later stage in a burner and its combustion test bench. The behavior of the torch in reactive conditions, i.e. with pulverized solid biomass injection in air, is currently under study. The first results obtained are very encouraging in terms of combustion efficiency. The different biomass fuels injected at different sizes of pulverization (wood, dried sewage sludge) are nearly 100% burned (conversion into CO2 and H2O) even though the biomass flow rate is low compared to the plasma power because of the limitation of the thermal power capacity of the test bench. The test bench is equipped with a special window in order to visualize the plasma and the generated flame with a high-speed camera. The flame obtained is extremely stable and the erosion rate of the torch electrodes is of the same order of magnitude as in neutral condition operation thanks to the active thermo-chemical gas sheathing technique set-up. A complete experimental study of biomass combustion will be reported in a next paper.

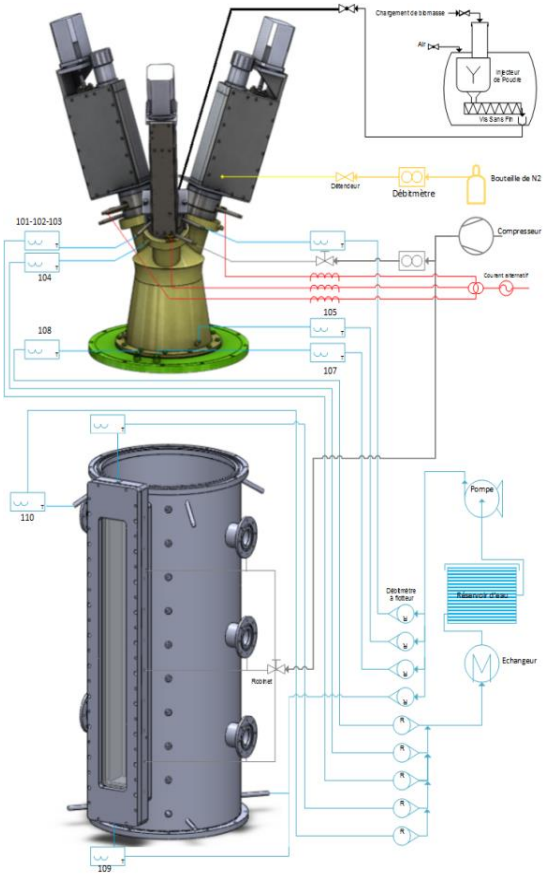


Figure 7: Drawings of the three-phase AC plasma torch and its biomass combustion test bench.

8- CONCLUSION

In the current context of global warming, the use of poor LHV biomass and waste for heat and power production will certainly play a major role in the next coming years. Unfortunately, poor LHV feedstock suffers from a major weakness, particularly when in solid form: they can hardy burn in autonomous burners without an external assistance. For few years, a new alternative solution derived from the coal industry has emerged: the plasma assistance combustion. This solution is particularly attractive in the perspective low carbon electricity production thanks to large scale deployment of renewable energy.

The principle is based on the thermochemical activation of the combustion thanks to the use of a thermal plasma whose power generally does not exceed few percent of the combustion thermal power. Such systems, called plasma electro-burners present number of advantages versus traditional technologies among which: their ability to deliver and tune the enthalpy and/or temperature through an external energy supply with temperatures that cannot be achieved with combustion methods, their capacity to be an intense source of radicals in air, their very short dynamic response, their limited environmental impact (no direct CO2 emissions), their flexibility and ability to operate under very different atmospheres, and their compactness. Most plasma electro-burners technologies today on the market use DC plasma torches. These technologies suffer from many drawbacks among which: limited electrodes lifetime, poor reliability, important water cooling needs, need of AC/DC transformers, etc. leading to high CAPEX and OPEX.

With the objective to exceed these limits and reduce OPEX and CAPEX while increasing reliability, the Center PERSEE MINES-ParisTech has been working in the development of an original three-phase AC plasma technology to be integrated in a plasma electro-burner. This technology based on graphite electrodes was initially designed for operating under inert or reducing conditions (cracking of methane, gasification, etc.). The main barrier for using this technology under oxidizing conditions was linked with the huge electrode erosion in the presence of oxygen. This challenge has succeeded thanks to an active thermo-chemical gas sheathing of the graphite electrodes. This paper presents the state of art and the main achievements on the plasma technology with a special focus on the limitation of electrodes erosion. It paves the way towards the design of a future robust and flexible biomass plasma electro-burner.

REFERENCES

[1] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, et S. Brunner, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of Intergovernmental Panel on Climate Change. Cambridge University Press, 2014.

[2] Ministère de l'écologie, du développement durable et de l'énergie, « Rapport sur les progrès réalisés dans la promotion et l'utilisation des énergies renouvelables », Report. 2013.

[3] Haider Markus et Seguin Philippe, Chaudières de puissance, à déchets, à biomasse et de récupération, Techniques de l'Ingénieur, *Techniques de l'Ingenieur*, 2012.

[4] Z. Xingang, T. Zhongfu, and L. Pingkuo, Development goal of 30 GW for China's biomass power generation: Will it be achieved?, *Renew. Sustain. Energy Rev.*, vol. 25, p. 310‑317, 2013.

[5] B. M. Jenkins, L. L. Baxter, T. R. Miles Jr. and T. R. Miles, Combustion properties of biomass, *Fuel Process. Technol.*, vol. 54, n° 1‑3, p. 17‑46, 1998.

[6] T. Nussbaumer, Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction, *Energy Fuels*, vol. 17.

[7] L. Zheng, *Oxy-Fuel Combustion for Power Generation and Carbon Dioxide (CO2) Capture*. Canada: Canmet ENERGY Ottawa Research Centre, 2011.

[8] A. Skorek-Osikowska, L. Bartela, J. Kotowicz, et M. Job, Thermodynamic and economic analysis of the different variants of a coal-fired, 460 MW power plant using oxy-combustion technology, *Energy Convers. Manag.*, vol. 76, p. 109‑120, 2013.

[9] Y. Ju et W. Sun, Plasma assisted combustion: Dynamics and chemistry, *Prog. Energy Combust. Sci.*, vol. 48, p. 21‑83, 2015.

[10] Y. Ju and W. Sun, Plasma assisted combustion: Progress, challenges, and opportunities, *Combust. Flame*, vol. 162, n° 3, p. 529‑532, 2015.

[11] J. M. Bergthorson and M. J. Thomson, A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines, *Renew. Sustain. Energy Rev.*, vol. 42, p. 1393‑1417, 2015.

[12] S. S. Merola, L. Marchitto, C. Tornatore, G. Valentino, et A. Irimescu, Optical characterization of combustion processes in a DISI engine equipped with plasma-assisted ignition system, *Appl. Therm. Eng.*, vol. 69, n° 1‑2, p. 177‑187, 2014.
[13] A. Starikovskiy and N. Aleksandrov, Plasma-assisted ignition and combustion, *Prog. Energy Combust. Sci.*, vol. 39, n° 1, p. 61‑110, 2013.
[14] A.-M. Warris and F. Weinberg, Ignition and flame stabilization by plasma jets in fast gas streams, *Symp. Int. Combust.*, vol. 20, n° 1, p. 1825‑1831, 1985.
[15] A. Askarova, E. Karpenko, Y. Lavrishcheva, V. E. Messerle, et A. Ustimenko, Plasma-Supported Coal Combustion in Boiler Furnace, *IEEE Trans. Plasma Sci.*, vol. 35, n° 6, p. 1607‑1616, 2007.
[16] NFPA 85: Boiler and Combustion Systems Hazards Code. [On line]. Avalaible on: http://catalog.nfpa.org/2015-NFPA-85-Boiler-and-Combustion-Systems-Hazards-Code-P1208.aspx.
[17] A. Wang, H. Tang, S. Ji, Y. Wang, D. Tian, G. Wang, W. Ren, X. Chen, R. Shao, X. Zhang, et S. Ma, Plasma igniter with assembled cathode, EP1371905 B1, 01-dec-2010.
[18] V.E. Messerle, A.B. Ustimenko, and O.A. Lavrichshev, Plasma-assisted ignition and combustion of pulverized coal at thermal power plants of Kazakhstan, *Proceedings of the 2014 International Conference on Power Systems, Energy, Environment*, 2014.
[19] V.E. Messerle, A.B. Ustimenko, and E.I.Karpenko, Plasma Technology for Enhancement of Pulverized Coal Ignition and Combustion, *Proceedings of ISPC20*, Philadelphia, July 2011.
[20] P. M. Kanilo, V. I. Kazantsev, N. I. Rasyuk, K. Schünemann, et D. M. Vavriv, Microwave plasma combustion of coal, *Fuel*, vol. 82, n° 2, p. 187‑193, 2003.
[21] P. Bukowski, P. Kobel, W. Kordylewski, et T. Mączka, Use of cavity plasmatron in pulverized coal muffle burner for start-up of a boiler, *Rynek Energii*, n° 1, p. 132‑136, 2010.
[22] S. Galant, D. Rebuffat, M. Reybillet, and N. Martin, Réacteur haute température associé à une zone de plasmagenèse, en particulier brûleur mixte électricité-combustible, EP0130913 B1, 07-oct-1987.
[23] S. Leleu, J. Aschard, et A. Bouvier, « Electrobrûleur à gaz à apport d'énergie électrique et amorçage assisté », EP0457994 B1, 12-oct-1994.
[24] V.E. Messerle, E.I. Karpenko, A.B. Ustimenko, Plasma assisted power coal combustion in the furnace of utility boiler: Numerical modelling and full-scale test, *Fuel*, vol. 126, p. 294300, 2014.
[25] Boulos M.I., Fauchais P., Pfender E., Thermal plasmas: fundamentals and applications, vol 1. Plenum Press, New York, 1994
[26] Solonenko O.P., Thermal plasma torches and technologies, vol. 15, Cambridge International Science Publishing, Cambridge, 2006
[27] Fulcheri L., Fabry F., Takali S., Rohani V., Three Phase AC Arc Plasma Systems: A Review, *Plasma Chem. Plasma Process.*, Volume 35, Issue 4, Page 565-585, 2015.
[28] Bonet C., Contribution to the theoretical study of a refractory spheroidal particle evaporation in ac thermal plasma (in French), State Doctorate es Sciences Physiques defended on 28 April, 1973, CNRS, France (199 pages), CNRS registration n° A.O. 8262. Because this reference is not available in the Internet, the author (Fulcheri L.) is willing to send it to interested reader upon request.
[29] Anonymous, The graphite electrodes electro-burner (in French), Journée d'étude du 30 Octobre 1986, Thermal engineering society (Société Française des Thermiciens), pp 1–13. Because this reference is not available in the Internet, the author (Fulcheri L.) is willing to send it to interested reader upon request.
[30] Reybillet M., Bertin electro-burner: description and mockup tests (in French), Journée d'étude du 30 Octobre 1986, Thermal engineering society (Société Française des Thermiciens), 5 pages. Because this reference is not available in the Internet, the author (Fulcheri L.) is willing to send it to interested reader upon request.
[31] Fulcheri L., Schwob Y., From methane to hydrogen, carbon black and water., *Int J. Hydrogen Energy*, 20(3):197–202, 1995.
[32] Fulcheri L., Probst N., Flamant G., Fabry F., Grivei E., Bourrat X., Plasma processing: a step towards, the production of new grades of carbon black. Carbon 40:169–176, 2002.

[33] Fulcheri L., Schwob Y., Flamant G., Comparison between new carbon nanostructures produced by plasma with industrial carbon black grades. *Journal of Physics*, III 7:491–503, 1997.
[34] Fulcheri L., Schwob Y., Comparison between two carbon nanostructures furnace and acetylene blacks., *High Temp Chem. Process* 3:575–583, 1994.
[35] Gruenberger T., Gonzalez-Aguilar J., Fabry F., Fulcheri L., Grivei E., Probst N., Flamant G., Okuno H., Charlier J.C., Production of carbon nanotubes and other nanostructures via continuous 3-phase AC plasma processing. *Fuller Nanotub. Carbon Nanostruct.*, 12(3):571–581, 2004.
[36] Okuno H., Grivei E., Fabry F., Gruenberger T., Gonzalez-Aguilar J., Palchinenko A., Fulcheri L., Probst N., Charlier J.C., Synthesis of carbon nanotubes and nano-necklaces by thermal plasma process., *Carbon*, 42:2543–2549, 2004.
[37] Fabry F., Study of a plasma process for the synthesis of carbon black by high temperature hydrocarbons pyrolysis and product characterization (in French), PhD thesis defended on 6 July, 1999, University of Perpignan 251 pp.
[38] Ravary B., Thermal and Hydrodynamic modelling of a 3-phase plasma reactor, contribution to the development of an industrial process for the production of carbon black (in French), PhD thesis dissertation, defended on December 17, 1998, Ecole des Mines de Paris 156 pp.
[39] Ravary B., Fulcheri L., Bakken J.A., Flamant G., Fabry F., Influence of the Electromagnetic forces on momentum and heat transfer in a 3-Phase AC plasma reactor *Plasma Chem. Plasma Process.*, 19(1):69–89 Plenum Press, 1999.
[40] Ravary B., Fulcheri L., Fabry F. and Flamant G., Analysis of the behavior of the arcs in a three phase AC plasma reactor. In: Proceedings ISPC-13 (13th international symposium on plasma chemistry), 18–22 August, 1997, Beijing, China, Vol. 1, edited by C.K. Wu, Peking University Press, pp 219–225.
[41] Fulcheri L., Carbon Nanostructures by plasma (in French), Habilitation degree dissertation (HDR) defended on March 21, 2003. University of Perpignan, http://tel.archives-ouvertes.fr/tel-00550503.
[42] Rehmet C., Theoretical and experimental study of a 3-phase AC plasma torch associated to a gasification process (in French), PhD thesis dissertation defended on 23 September, 2013, MINES-ParisTech (196 pages).
[43] Rehmet C., Rohani V., Cauneau F., Fulcheri L., 3D unsteady state MHD modeling of a 3-phase AC hot graphite electrodes plasma torch. *Plasma Chem. Plasma Process.*, 33:491–515, 2013.
[44] Rehmet C., Fabry F., Rohani V., Cauneau F., Fulcheri L., A comparison between MHD modeling and experimental results in a 3-Phase AC arc plasma torch. Influ electrode tip geom, *Plasma Chem. Plasma Process.*, 34(4):975–996, 2014
[45] Rehmet C., Fabry F., Rohani V., Cauneau F., Fulcheri L., High speed video camera and electrical signal analyses of arcs behavior in a 3-Phase AC arc plasma torch., *Plasma Chem. Plasma Process.*, 33:779–796, 2013.
[46] Rehmet C., Fabry F., Rohani V., Cauneau F., Fulcheri L., Unsteady state analysis of free-burning arcs in a 3-phase AC plasma torch. Comparison between parallel and coplanar configurations, *Plasma Sources Science and Technology*, 23 065011 12 pp, 2014.
[47] Takali S., Etude théorique d'un électrobruleur industriel dote d'une torche à arc triphasée pour la valorization énergétique de combustibles à faible pouvoir calorifique (in French), PhD thesis dissertation defended on 02 December, 2015, MINES-ParisTech (227 pages).
[48] Jones W.P., R.P. Lindstedt, Global reaction schemes for hydrocarbon combustion, Combust. Flame, vol. 73, 3, p. 233-249, 1998.