APPLICATIONS OF PLASMA TECHNOLOGY IN ENERGY SECTOR

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Abstract

Today, the use of plasma technology in production of energy from waste, biomass and coal has become quite widespread in the world due to the unique and outstanding features of plasma. Experimental and theoretical studies have shown that plasma based system in energy production is a promising alternative to classical system in terms of efficiency, environmental and economic aspects. Plasma assisted combustion, gasification and pyrolysis are different methods used in energy production. Considering the plasma technology applications in energy sector, it is widely used in developed countries like Europe and USA for the energy production from the waste and biomass, but plasma is generally preferred in eastern countries like China, Kazakhstan and Russia for plasma coal gasification and plasma assisted coal burning at thermal plant. Different plasma torch systems (AC, DC and RF) used in these applications are seen in the literature. This paper gives an overview on plasma technologies in energy production from different energy sources (waste, biomass, coal) by different techniques such as combustion, gasification and pyrolysis. In comparison of AC, DC and RF plasma torches in the scientific literature, it has been considered that AC plasma torch is a prominent technology due to some advantages especially in high power as megawatt levels. Lastly, economic assessment is presented and estimated budget for system installation is given for different systems. Although the technology readiness level of the plasma technologies has a level of maturity (over 6) in our facilities at AR&TeCS (ARTECS Inc., Ankara University Technopolis, Gölbaşı, Ankara), the application on the different type of waste management or plasma assisted coal burning/gasification needs some additional R&D activities especially in simulation and modelling for obtaining optimum conditions, process development and controlling of gasification/combustion process. Finally, some technical experience from the high-power alternating current (AC) plasma system established at AR&TeCS is shared.

Key Words: Plasmatron, High power, Alternative Current, AC, Coal, Biomass, Waste, Gasification

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PLAZMA TEKNOLOJİSİNİN ENERJİ SEKTÖRÜNDEKİ UYGULAMALARI

Özet

Günümüzde, plazmanın benzersiz ve olağanüstü özelliklerinden dolayı atık, biyokütle ve kömürden enerji üretiminde plazma teknolojisinin kullanımı dünyada oldukça yaygınlaşmıştır. Deneysel ve teorik çalışmalar, plazma bazlı sistemin enerji üretiminde klasik sisteme verimlilik, çevresel ve ekonomik açıdan umut verici bir alternatif olduğunu göstermiştir. Plazma destekli yanma, gazlaştırma ve piroliz, enerji üretiminde kullanılan farklı yöntemlerdir. Enerji sektöründeki plazma teknolojisi uygulamaları göz önüne alındığında, atık ve biyokütleden enerji üretimi Avrupa ve ABD gibi gelişmiş ülkelerde yaygın olarak kullanılmaktadır ancak plazma kömür gazlaştırma ve plazma kömür yakma genellikle Çin, Kazakistan ve Rusya gibi doğu ülkelerinde tercih edilmektedir. Bu uygulamalarda kullanılan farklı plazma sistemleri (AC, DC ve RF) literatürde görülmektedir. Bu makale yakma, gazlaştırma ve piroliz gibi farklı tekniklerle farklı enerji kaynaklarından (atık, biyokütle, kömür) enerji üretiminde plazma teknolojileri hakkında genel bir değerlendirme vermektedir. AC, DC ve RF plazmatronlar bilimsel literatürde karşılaştırıldığında; AC plazmatronun özellikle megawat seviyelerindeki yüksek güçlerde bazı avantajlardan dolayı önemli bir teknoloji olduğu düşünülmektedir. Son bölümde, ekonomik değerlendirme ve sistem kurulumu için tahmini bütçe farklı sistemler için verilmektedir. AR&TeCS'de (ARTECS A.Ş., Ankara Üniversitesi Teknokent, Gölbaşı, Ankara) kurulu laboratuvarlarda, plazma teknolojilerinin teknoloji hazır olma seviyesi olgunlaşmış (6 üzerinde) olmasına rağmen, farklı atık yönetimi tipi veya plazma kömür yakma/gazlaştırma uygulamaları, özellikle optimum koşulları elde etmek, süreç geliştirme ve gazlaştırma/yanma sürecinin kontrolü için simülasyon ve modellemede bazı ilave Ar-Ge faaliyetlerine ihtiyaç duyulmaktadır. Son olarak, tesislerimizde kurulu olan yüksek güçlü alternatif akım plazma sisteminden elde edilen bazı teknik deneyimler paylaşılmaktadır.

Anahtar Kelimeler: Plazmatron, Yüksek güç, Alternatif Akım, AC, Kömür, Biyokütle, Atık, Gazlaştırma

1. INTRODUCTION

Recently, the applications of plasma technology are becoming widespread due to its interesting and superior properties. Although the usage of electric fields to plasma has been started in 1814, plasma combustion was applied in the 1920's and further applications was implemented in the last half of the 20th Century [1].

Plasma is an ionized gas, consisting of a mixture of electrons, ions and neutral particles and described as a fourth state of matter. A plasma can be defined as "quasi-neutral" which means that it is neutral enough that electron density nearly equals ion density, but not so neutral that all interesting electromagnetic forces vanish [2]. Plasmas can be classified as thermal and non-thermal plasmas according to ionization levels and temperature differences between heavy particles and electrons [3, 4]. Thermal plasma has many advantages in terms of high energy density, high temperature and high enthalpy. So, it has been used in variety areas such as metallurgy, cutting, welding, etching, scientific research and more efficient production of energy from different types of wastes, biomass and especially low quality coal via plasma assisted combustion, plasma gasification and pyrolysis [3, 5].

With increasing population and industrialization, all types of wastes including hazardous, industrial, medical and municipal solid waste have increased in worldwide and efficient waste management has become an important issue. In addition, waste has been considered as an important renewable energy source and different methods have been applied in waste treatment which are combustion/incineration, gasification and pyrolysis. Combustion is an exothermic process that takes place in an oxidizing environment converting hydro carbonaceous materials into product gases. The role of plasma in combustion can be by means of different ways including thermal, chemical and transport phenomena. On the thermal side, due to the high temperature of plasma, the chemical reactions are accelerated. Chemically, plasma can play a major role to increase the yield in the chain of combustion and oxidation mechanics due to the reactive radicals and species such as O, OH and H contained in it. Also, plasma can attend in completely breaking of big fuel molecules indirectly [6]. Similarly, plasma in gasification breaks down waste into simple gaseous molecules such as carbon monoxide and hydrogen. But, gasification process is performed in an oxygen starved environment to avoid the combustion of carbon to CO_2 [7]. On the other hand, pyrolysis process takes place with no oxygen unless partial combustion is needed to provide the thermal energy needed for this process [8].

Recently, many research and development activities have been focused on conversion of waste into energy and processes that minimize emissions and integrate the life-cycle assessment of technologies and materials [9]. Plasma technology is considered as a highly attractive method for the processing of all waste types including hazardous wastes with its high temperature, enthalpy and the residence time [10].

On the other hand, coal is still considered as one of the main energy resources of 21st century. But decreasing of quality and power of coals such as Turkey's big lignite source has led to the difficulties in ignition and incineration of it and increased the emissions of hazardous air pollutions. In order to improve the efficiency of coal combustion, plasma technology has been started to be used in thermal-power plants in some countries [5]. Plasma-assisted pulverized coal combustion technology has been tested successfully on 27 pulverized coal boilers in 16 TPP (Thermal power plant) located in Russia, Kazakhstan, Korea, Ukraine, Slovakia, Mongolia and China. These tests clearly show the advantages of PFS system which are quick start-up, the ease of safe flame stabilization, high efficiency and decreased hazardous emissions [11].

Gasification of coal is also considered as one of the most important and effective ways for converting coal into high energetic gases, called as "syngas" and then to useful chemicals, or to electricity through the processes of syngas [12]. The use of plasma technologies in coal gasification provides an efficient and environmentally friendly way for power generation compared to the classical methods [13].

In Turkey, recent studies show that lignite reserves have reached to 15.9 billion tons [14]. Due to the energy dependency, Turkey has very strong desire to develop new technology and process to use its lignite reserves efficiently. But, because of their mostly low quality and high moisture content, coals cannot be effectively burned using classical systems [15]. The temperature level of classical incineration using fuel oil is about 1100 K [16]. High temperature, over 2000 K and chemically active species generated by plasma torches is very effective in a complete coal combustion [17, 18].

In addition to the huge lignite reserve, approximately 25.800.000 tons of wastes are generated in one year in Turkey. With increasing population, Turkey aims to maximize the economic opportunities in waste management while minimizing negative environmental effect focusing on new, clean and effective technologies in energy production from waste [19]. At that point plasma is one of the most important technologies to be applied.

Plasma technology has many advantages compared to auto thermal processes in waste treatment. Firstly, plasma reaches high temperature comparing to classical systems and plasma contains high concentration of energy in a small volume of it and high rate of the chemical reactions [20]. The high-energy density and temperature of thermal plasma offer high efficiency even in a small reactor [21]. Plasma technology requires compact equipment with small size and the control of operating regime is achieved simply and automatically allowing short startup and shutdown times [20, 21, 22]. In plasma technology, enthalpy control is easily established by adjusting the electrical power which is not possible in conventional systems [10].

In addition, plasma technology is an environmentally friendly technology reducing the hazardous emissions like tar, CO_2, CH_4 and higher hydrocarbons, NO_x and SO_x [23]. Thus, plasma technology has been a favorable alternative to other conventional combustion and gasification technologies.

2. PLASMA APPLICATIONS IN ENERGY PRODUCTION FROM WASTE

World Bank has declared that currently about 4 billion tons of all types of waste (1.5 billion tons of solid waste) are produced throughout the world per year and it is expected to reach to 2.4 billion tons until 2025 [24]. The simple waste treatment method currently in use is landfilling. Since landfilling method has become increasingly expensive and difficult to comply with new environmental regulations, waste to energy facilities have been become widespread [22]. Also, landfills with methane emissions were recently defined as a main reason of global warming [18]. In Europe, landfill is considered as a missed chance and it is planned to landfill less waste, produce more energy from waste [25, 26, 27]. Figure 1 shows the methods used for MSW management in the EU in 2003. In Netherland and Denmark, almost no MSW to landfill is disposed, and in Belgium, Sweeden, Germany and Luxembourg all landfill is less than a quarter of their MSW [27].

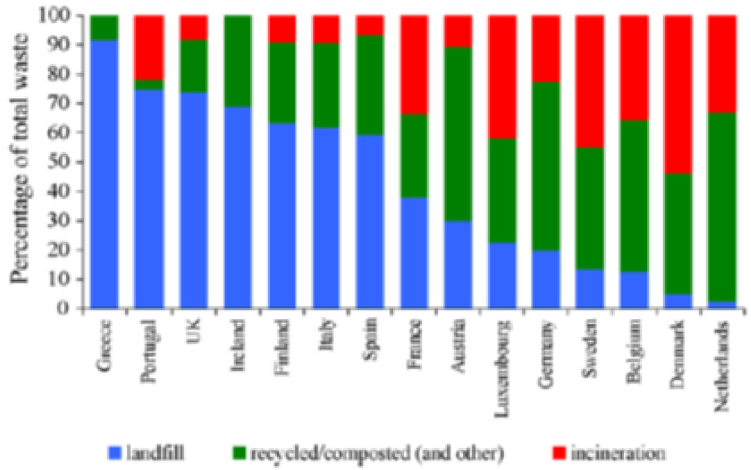

Figure 1. Municipal waste management in the European Union in 2003 [27].

As mentioned above, the amount of collected municipal waste in Turkey is about 25.800.000 tons per year and 29% of MSW is disposed via dumpsite and 71% of it is placed in landfill and used in compost facilities to produce energy. The total power capacity of licensed facilities that generates energy from the landfill gas is approximately 95 MWe. There are three biomethanization facilities (Ankara, Adana and Pamukova/Sakarya) with ~147 MWe power capacity that produced energy from biomass. Turkey population growth rate is 13% between 2004-2013 and population of Turkey has reached to about 78.741.000 million at the end of 2015 [19]. Parallel to the increase in the population, the waste amounts increased as expected. The industrialization has created main source of hazardous waste, and the amount of hazardous waste was reportedly reached to about 1.423.000 tons in 2015 [28]. In order to eliminate hazardous waste by producing energy, new investments are planning to increase production of energy from waste with an efficient and clean technology [19].

In all over the world, it is very essential that energy is produced from waste effectively through the most efficient and clean technologies including anaerobic digestion, mechanical and biological treatment processes (MBT), direct combustion or incineration and advanced thermal treatment (ATT) processes as gasification and pyrolysis [27]. The following figure shows that the landfilling is decreasing in the EU-27 countries in time and the use of other methods is increasing in waste treatment.

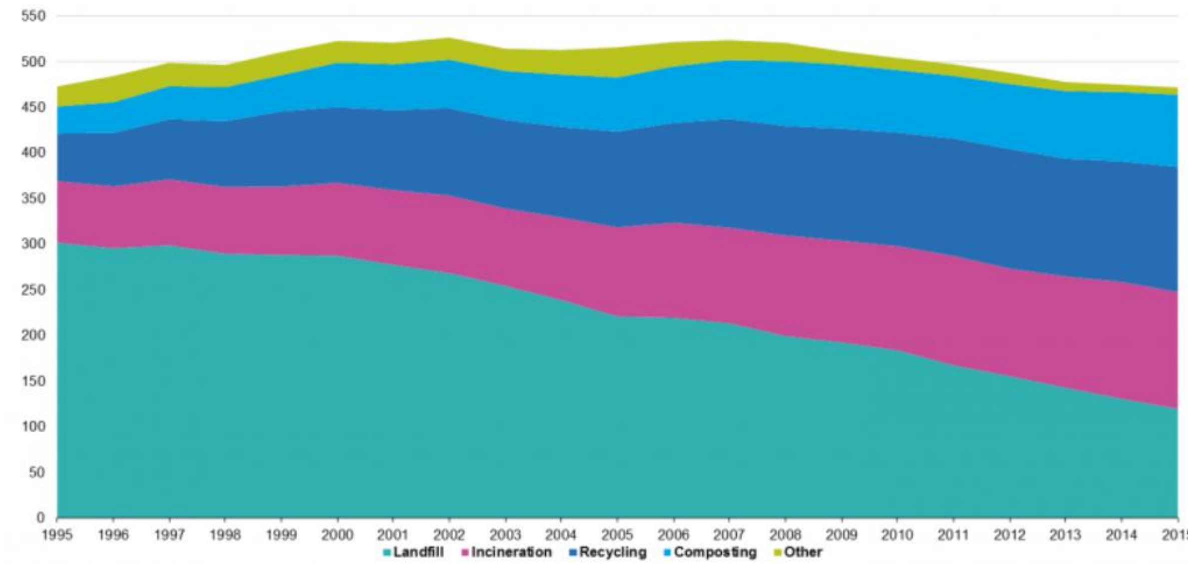

Figure 2. MW treatment by type of treatment, EU-27, (kg per capita), 1995–2015 [29]

Waste management is a major issue in many countries because of increasing amount of MSW and industrial waste. For example, in Japan, due to increasing difficulty to get suitable sites for landfill, combustion has become an important method for waste treatment. However, because a considerable amount of hazardous reaction products such as dioxin, heavy metals come out in conventional combustion and incineration processes, more appropriate treatment method have been searched for the sake of safe environment. So, in Japan, plasma treatment which destroy toxicity has been started to study and to apply in these processes [30]. In Utashinai, there is the only commercial plasma arc facility that treats MSW worked by Hitachi metals and Alter NRG. Now, there are 87 operational WTE plasma power plants with 2500 MW or about 0.3% of total national power [22].

The development of plasma gasification process for waste disposal began in the USA, Europe and Japan in the 1980s. Now, more than 150 industrial gasifiers which are mainly used process biomass and coal were built throughout the world [22]. Table 1 shows some of thermal plasma plants in the EU, the USA and Asia.

Table 1. Thermal plasma plants in the EU, the USA and Asia [21, 10, 31]

Location	Material	Capacity (TPD)	Date
Europe			
Landskrona,Sweden	Fly ash	200	1983
Bordeaux, France	Ash from MSW	10	1998
Morcenx, France	Asbestos	22	2001
Morcenx, France	-	137	2012
Kedzierzyn-kozel, Poland	ISW	10	2001
Bergen, Norway	Tannery waste	15	2001
Kozloduy, Bulgaria	LLRW	5	2010
Hirwaun,UK	MSW/Industrial	~750	2015
Moscow, Russia	LLRW	6.0-9.5	2002
America			
Anniston, Albama	Catalytic converters	24	1985
Jonquiere, Canada	Aluminum dross	50	1991
Honolulu, Hawaii	Medical waste	1	2001
Richland, Washington	Hazardous waste	4	2002
Alpoca, West Virginia	Ammunition	613	2003
USA Navy	Shipboard wastes	7	2004
USA Army	Chemical agents	10	2004
Hawwthorne, Nevada	Munitions	10	2006
Ottawa, Canada	MSW	85	2007
Los Angeles, USA	Biomass, Const. waste	18	2009
Hurlburt Field, USA	MSW/Hazardous	10.5	2011
Asia			
Kinura, Japan	MSW Ash	50	1995
Yoshi, Japan	MSW	151	1999
Mihama-Mikata, Japan	MSW/Sewage sludge	28	2002
Utashinai, Japan	MSW/ASR	300	2002
Shimonoseki, Japan	MSW Ash	41	2002
Kakogawa, Japan	MSW Ash	31	2003
Imizu, Japan	MSW Ash	12	2002
Maizuru, Japan	MSW Ash	6	2003
Lizuka, Japan	Industrial waste	10	2004
Taipei, Taiwan	Medical and battery waste	4	2005
Osaka, Japan	PCBs (Poly chlorinated Biphenyl)	4	2006
Cheongsong, Korea	MSW	10	2008
Pune, India	Hazardous waste	68	2009
Nagpur, India	Hazardous waste	68	2010

2.1. Comparison of Classical Incineration and Thermal Plasma Gasification

When we compare classical incineration and thermal plasma gasification, incinerations have large quantity of excess air, but thermal plasma gasifiers add a limited quantity of O_2. Incinerations are designed to maximize CO_2 and H_2O, but gasifiers are designed to maximize CO and H_2. Because of oxidizing environment inside the incineration furnace, NO_x and SO_x are generated in incineration process, but due to the reducing environment, NO_x and SO_x generation are prevented. Temperatures in processes are also different in both processes. Although, temperature of incineration furnace is around 800 °C which is below an ash melting point causing inorganic materials in MSW turn into fly ash, temperature of gasification processes can be adjusted above 1500 °C which is above an ash melting point that provides inorganic materials in MSW to transform to vitrified slag which can be used as a source of building materials [3]. Also, pyrolysis is more advantageous than incineration in terms of some reasons. Combustion of syngas resulting from gasification or pyrolysis with almost no ashes left is much more ecologically highly beneficial in comparison with methane due to incineration. Throughout pyrolysis and gasification, less toxic compounds such as dioxins, furans, carbon monoxide and ashes are generated [18].

2.2. Plasma Waste Gasification System

An example of concept of the plasma gasification schematic under consideration by AR&TeCS is given in Figure 3. In a plasma gasification system, all types of waste, fossil fuels and biomass can be used as feedstocks. Plasma torch is used as an energy source with high enthalpy, residence time and high temperature. In gasification process, plasma gasification environment is an oxygen starved. Output gas is supposed to be cleaned to form pure syngas and it can be used for renewable energy production like natural gas or as precursor for many chemicals through some conversion processes [16].

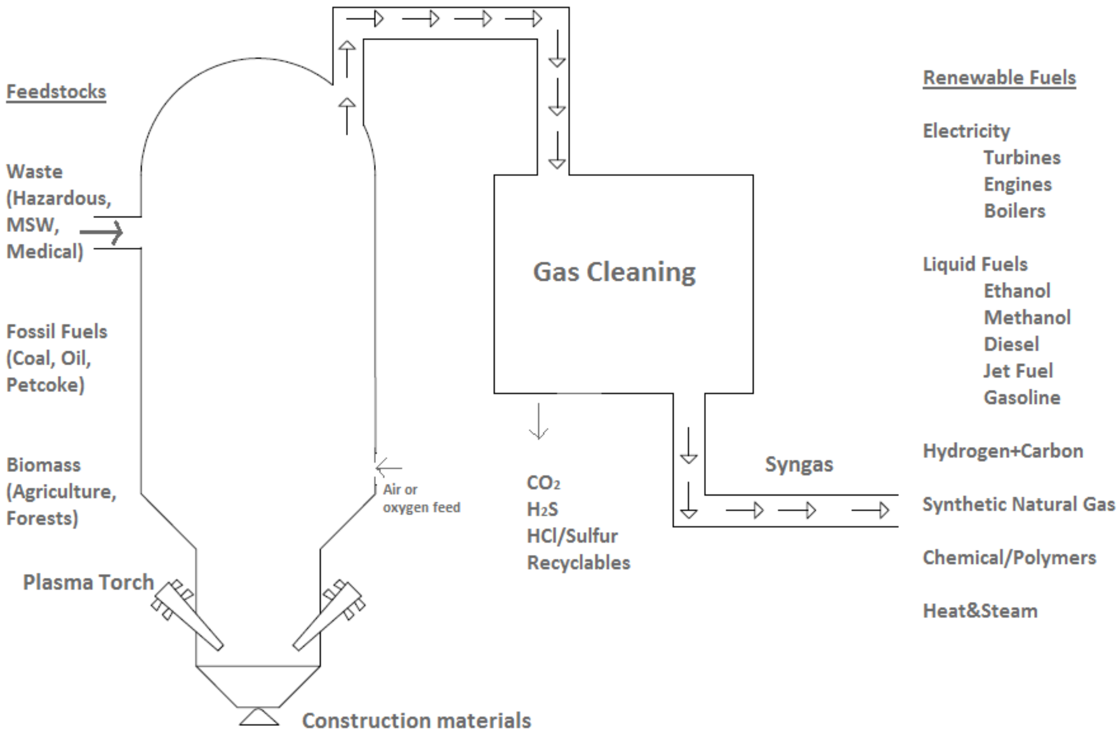

Figure 3. Schematic of plasma gasification system

Syngas can be used as the raw material by low Btu reciprocating engine generators, gas turbines and boilers to produce fuel. Also, it can supply essentials to form methanol, ethanol, butanol, gasoline, diesel, plastic and many other carbon based products that are generated from crude oil [10, 32, 33, 34, 35].

Another advantage of syngas is that CO and H_2 in its content can be used as feedstock for the output of synthetic liquid fuels in operation. Hydrocarbon conversion operating syngas for the hydrogen yield is to be used for hydrogen production in fuel cell engines. An experimental study shows that hydrogen conversion of syngas in waste treatment is higher than that of classical incineration. That can be used for hydrogen production in fuel cell [18].

Moreover, plasma waste treatment compared to classical incineration is more efficient in terms of electricity generation. Using a boiler with steam turbine, net electrical efficiencies are achieved from 18% to 22% [27]. Whereas, syngas produced by plasma gasification process can recover up to 80% of the chemical energy included in the organic substance initially processed and so a plasma gasification system with a gas turbine combined cycle power plant can aim up to 46.2% efficiency [36].

3. PLASMA APPLICATIONS IN ENERGY PRODUCTION FROM COAL

Coal is still considered as one of the main energy resources of the 21st century [5]. According to the World Energy Council, there are coal reserves in around 80 countries. Some of the coal rich countries are the USA with the largest amount of coal reserves as 237.3 billion tons, Russia Federation with 157 billion tons, China with 114.5 billion tons and Australia with 76,4 billion tons. Turkey is considered as a medium level in terms of reserve of lignite with about 15 billion tons [15]. The fraction of coal-fired thermal power plants in electrical power generating is about 60% in the USA and Germany [36] and is about 85% in the Kazakhstan [5], 87% in China and 47% in Turkey [37, 38].

However, because of the decreasing quality of coal, the difficulties of its ignition and environmental problems have been arisen. To increase the efficiency of coal combustion and solve the environmental pollution problems, new plasma fuel-system for the thermal power plant for low quality coal is developed [5]. Plasma technology providing thermal plasma with its high temperature and high number of active species, improves the efficiency of combustion of coals while reducing the need of additional fuel oil and/or natural gas in the fuel balance of thermal power stations and harmful gas emissions. Plasma-fuel systems (PFS) have been constructed and tested in different countries as Russia, Kazakhstan, Ukraine, China, Korea, Slovakia, and Mongolia in 29 boilers with steam outputs ranging from 75 to 670 t/h. [37]. There are three generations of plasma ignition systems which were designed and tested. First generation plasma igniters which had a plasma torch with a moving graphite-rod cathode and a water-cooled annular copper anode were mounted on the Ch-200 boiler at the Baoji TPP. First-generation plasma igniters have been retrofitted and spread in China to have more boilers with an installed capacity above 160x106 kW by the Yantai Longyuan Electric Power Technology Company (China). Second-generation plasma igniters with plasma torches having replaceable water cooled copper cathode and anode were tested at the Shaoguan TPP (China) in 2000-2001 and third-generation ones with the oscillation-free startup of plasma torches were tested at the Shenyang power station golden mountain in 2007 [38]. These three generations of PFS developed and tested at thermal power system (TPS) in different counties are summarized in Table 2 [37].

Table 2. Commercial tests of PFS at TPS [37]

TPS (Location)	Test Years	Quantity of boilers with PFS, pcs.	Steam capacity of one boiler, t/h.	Quantity of PFSs at the TPS, pcs.
Russian Federation				
Gusinoozerssk, Suvorov, Neryungri, Partizansk Khabarovsk	1994-1998	1-2	170-670	2-8
Ukraine				
Mironovka Kurakhovo	1989 1998-1999	1	230-670	2-4
Kazakhstan				
Alma-Ata Ust-Kamenogorsk	1996 1989	1-2	75-160	4-2
Mongolia				
Erdenet Ulan-Bator	1994 1995	1-8	75-420	1-16
China				
Baodi Shaoyang	1995 1999-2001	1	75-230	1-4
North Korea				
Pyongyang	1993	1	210	3
Slovakia				
Velky Kapushany	2000	1	350	2

4. DIFFERENT PLASMA TECHNOLOGIES

Different plasma torches types such as DC, AC, and RF can be used in plasma applications in the energy sector. Mainly, four companies which are Westinghouse, Europlasma, Tetronics and Phoenix Solutions Company (PSC) dominate the current market for high power plasma torches. Generally, DC plasma torches are developed by these companies. Westinghouse, Euro plasma and PSC developed transferred and non-transferred DC torches with water cooled metal electrodes. Differently, Tetronics developed a transferred DC torch with two graphite electrodes which are not water cooled [10]. Also, other different plasma torch technologies have been developed in some research laboratories such as Applied Plasma Technologies (USA), PERSEE-MINES Paristech (France) (MINES ParisTech), Institute for Electrophysics and Electric Power (Russian academy of sciences), Keldysh Research Center [39, 40], Von Karman Institute (ICP plasma torch) [41] and in

ARTECS facility (Turkey) collaboratively with Keldysh Research Center [42].

4.1. DC Plasma Torches

DC plasma arc generally consists of three parts, the cathode region, the anode region and the arc column. The plasma is generated between two electrodes and the resistance of the plasma is used to convert electricity into heat energy [3]. This technology is not new. Westinghouse established in 1970's began producing plasma torches for National Aeronautics and Space Administration (NASA) to be used in simulation of entry conditions in the atmosphere within the scope of space program "Apollo" [10].

There are two kinds of plasma arc which are transferred and non-transferred DC plasma torches. [3, 43]. In the transferred plasma arc, firstly the small plasma arc is ignited between the electrode and the nozzle and then it is transferred to the work piece to be a big arc by the plasma jet and one of the plasma forming electrodes is included within any single torch body. On the other hand, after the non-transferred plasma arc is ignited between the electrode and nozzle, continuous working gas and the high temperature plasma jet is occurred [44, 45]. Plasma arc is created outside the water-cooled body of the torch so transferred arc torches can generate extremely high thermal fluxes and radiant heat transfer losses to the cold torch body are reduced. Thus, the transferred arc plasma torch is inherently more efficient than the non-transferred arc torches [44].

Non-transferred DC plasma torches are separated into two groups which are hot (thermionic) cathode torches and cold cathode ones which is not electrically heated. Typically, hot (thermionic) cathode DC torch with a water-cooled ring anode is used for thermal spray coating applications. Thoriated tungsten is normally used as the cathode material. Generally, cold cathode is preferred in plasma gasification and chemical processes [45]. Europlasma plasma torches are mainly based on cold cathode DC torches [10]. Mostly, copper and copper alloy are used for cold cathodes worked with arc current limited to 1200-1500 A and copper erosion exists too much. Also, different supplies such as low carbon steel, titanium, stainless steel and copper-nickel alloys and tungsten have been used as cathode materials [46].

Lifetime of electrodes is important for these plasma torch processes and the cathode erosion rate is the limiting factor. Found that both the arc rotation and type of gas mixture has a significant effect on erosion rate. For example, if the arc rotation speed is increased from around 5-80 m/s, the cathode erosion rate of an argon-nitrogen arc operated at 100 A is reduced by one order of magnitude. Also, it is shown that the addition of only 1% nitrogen to argon strikingly decreased the erosion rate [47, 48]. Different studies are being carried out to increase the electrode lifetime. In general, revealed that cathode material, plasma forming gas composition, efficiency of the gas vortex, magnetic field configuration and arc current affects the erosion rate of cold cathodes [46].

The plasma plume of DC plasma torches has generally high velocity (several hundred ms^{-1}) and high temperatures (10000-20000 K). DC plasma torches are exposed to severe thermal, mechanical and even chemical effects so that they have a critical drawback which is inevitable electrode erosion which limits the electrode lifetime. Also, DC plasma torches need delicate and costly power supply electronics for AC-DC current rectification which is another disadvantage of them [39].

4.2. RF Plasma Torches

The first demonstration of the continuous working of inductively coupled radio frequency discharged RF torches was realized in 1961 at Lincoln Laboratory, Massachusetts Institute of Technology [49]. RF plasma torches have no electrodes so the plasma is not polluted by the metallic vapors [44]. RF discharges is excited and sustained by high-frequency electromagnetic fields. Power coupling in RF discharges is performed in different ways which are capacitively and inductively coupled discharges. High frequency RF electric fields (typically 13.56 MHz) creates capacitively coupled plasma (CCP). RF system comprises of a generator and the reactor with electrodes. Inductively coupled plasma (ICP) is similar with CC. But the electrode has a coil which generates electromagnetic field inductively exciting the plasma.

RF inductively coupled plasma torches commonly available at power levels of 100 kW and mainly applied in the field of spectro-chemical analysis, synthesis of high purity silicon or titanium dioxide pigments, and ultra-fine and ultra-pure powder synthesis [44]. There is an example of large scale (1.2 MW) inductively coupled plasma (ICP) which are constructed at Von Karman Institute by funded European Space Agency (ESA) to be used in re-entry tests [41].

In the sense of RF plasma technology, another study shows that the scale up of it to the hundreds of kW level, closer to the 500 kW or 1MW and developing the novel powder injecting techniques in forming plasma will be major improvements of the processing capabilities of the technology

[45].

Because it is considered that a major drawback of DC plasma torches is the short lifetime of the cathode and this problem can be solved by RF technology, the development of high power hybrid RF and DC plasma torches are worked by Applied Plasma Technologies (APT). A hybrid plasma torch (RF+DC) have been developed with a good energy efficiency (between 80 and 95%) for a power of 150 kW [50]. In conclusion, although this technology is advantageous due to having no electrode erosion, now, they are commonly available with limited power levels with high investment costs [10].

4.3. AC Plasma Torches

AC arc plasma studies have been performed to get high enthalpy gas flows almost simultaneously in the United States and in the former Soviet Union for the need of simulation of high temperature re-entry since 1960s [39]. In recent years, alternating current (AC) plasma torches have been used more extensively in different types of plasma technologies mostly for the application of high-power plasma generators. In this type of plasma torches, plasma is generated by the energy of AC current of industrial frequency by heating the gas. Different than the ballast resistance in DC arc plasma torches for the stabilization of DC arc, inductance coils (reactors) stabilize and regulate the operating regime of the AC plasma torches, to this respect the electrical power is simplified and the price is reduced [20].

AC plasma torches consist of mainly single phase and three phases torches. Different works have been done in USA, Russia, France, Norway, Germany and Japan for about 50 years [39]. Rutberg's group of Institute for Electrophysics and Electric Power at the Russian Academy of Sciences in St. Petersburg has conducted considerable researches on the three-phase AC technology in the former Soviet Union, later Russia [18, 51]. In Russia, a new design of three-phase AC plasmatron called "Zvezda" was developed in Keldysh Research Center as the three-arc and six-arc versions with the power of 1MW and 30 MW, respectively. In these plasmatrons, it is shown that the lifetime of electrode which is the main parameter to determine the working time of plasmatron can reach 500 h [40].

In Turkey, the high-power AC plasmatron test system has been established in AR&TeCS (ARTECS Anadolu R&D Technology Engineering and Consultancy Company, Ankara University

Technopolis) and qualification tests have been performed with Keldysh Research Center (Moscow, Russia) cooperation in October, 2016 [42, 52].

In France, MINES-Paris Tech and TIMCAL worked collaboratively between 2004 and 2009 to develop the AC plasma technology. PERSEE-MINES ParisTech have researched on three-phase AC plasma technology to apply in gasification and assisted combustion since 2009. Experimental and theoretical studies of the three-phase AC plasma system was conducted by two PhD thesis in 2013 and 2015 in France [53, 54].

Because of some weaknesses of DC plasma torch technologies which are limited lifetime causing to a lack of robustness, poor/limited reliability due to plasma stability, strong water-cooling needs, and need of AC/DC transformers with high costs, an three phase AC plasma technology has been developed to be integrated in a plasma electro-burner by the Center PERSEE MINES-ParisTech [6].

Although the application of alternating current brings additional difficulties caused by the variability with time of electrical parameters of the power source, AC plasma torches have some advantages comparing to DC plasma technologies especially in higher power as megawatt level, rectifiers of DC plasma torches are very complicated and expensive but AC plasmatrons do not require such complicated devices and are preferred in the application of high power levels. Also, electrode lifetime is higher in AC plasmatrons [20].

5. EFFICIENCY

General system efficiency is defined as the ratio of the net generated electricity to the energy input to the system:

$$System\ efficiency\ [\%] = \frac{Power\ \ output\ \ [MW]}{Energy\ \ input\ \ to\ system\ \ [MW]} x100 \tag{1}$$

After all, to get these values, the combustion and gasification efficiencies, besides the performance of the different prime moves, i.e. steam turbines, gas engines and CCGT units, are to be acquired [27].

To compare the performances between conventional systems and plasma gasification systems, different criteria can be used such as cold gas efficiency, LHV (Lower heating value) of the syngas and the net electrical efficiency [10].

Especially in thermal design of classical systems, composition of the fuel (feedstock) besides its energy content which are defined by ultimate analysis, proximate analysis and heating values are crucial [8]. It is important to normalize the quantities of the fuel (MSW, feedstock) and concerned elements, as well as to verify that they are based on either the lower heating value (LHV) or higher heating value (HHV) of the fuel (MSW) [55]. Proximate analysis gives the composition of the MSW in terms of fixed carbon, volatiles and ash contents, moisture as well as its lower heating value (LHV). Ultimate analysis shows the elemental compositions of the waste on a dry ash free basis, in terms of carbon, hydrogen, oxygen, nitrogen, Sulphur and chlorine [27]. Ultimate analysis is found more difficult and expensive in comparison to proximate analysis and some standard methods are introduced for determination of the ultimate analysis of biomass components [8]. Also, for ultimate and proximate analysis, it is recommended that calculated data and measured data are used in common. Especially for biomass and waste feedstock, calculated and measured data may easily deviate by over 5%, so measured data must be verified carefully [55].

Low heating value is described by the following formula [56];

$$\sum\left(LHV\ of\ combustible\ component\left(\frac{MJ}{Nm3}\right)x\ concentration\ of\ component\ (\%)\right) \qquad (2)$$

With relatively long residence time for gas in the gasifier and high temperature of plasma gasification, tar products are broken and hazardous yields such as dioxin and furan are to be disposed. Because of low tar content in the syngas, better net electrical efficiency can be provided in plasma systems than auto thermal processes. High temperature also admits synthesizing and degrading chemical species and highly precipitate the chemical reactions. The reactive species generated by plasma such as atomic oxygen and hydrogen or hydroxyl radicals, also, enhance the efficiency of process [10, 8]. That can be seen in literature that these species increase strongly the degradation of the tars with higher efficiency than classical processes [57, 58]. In addition, plasma gasification is relatively insensitive to the content and quality of the feedstock [10, 8].

Plasma is advantageous compared to conventional system in terms of material yield, syngas purity, energy efficiency, dynamic response, compactness and flexibility. Enthalpy is supplied by plasma power which can be regulated independently of the heating value of the feedstock making the process independent of the ratio O/C and the nature of the plasma medium (neutral, oxidizing or reducing atmosphere. On the other hand, precise control of the enthalpy is not permitted in classical system [10].

Performing the mass and energy balances enable the comparison of the technical performance of the different waste treatment methods by determining their overall system efficiencies. The fuel gas production which is the flow of the gas mixture generated by gasification per kilogram of product (Nm^3/kg) are given as the following when air is used as oxidant in the reactor [56].

$$Fuel\ gas\ production\ (Nm^3/kg) = \frac{air\ \ flow\ \ rate\ \left(Nm^3/s\right)\ x\ 0.79}{\left[[1-(CO+CO_2+H_2+CH_4+C_2H_4/100]\ x\ feeding\ \ rate\ \ (kg/s\right]} \qquad (3)$$

Energy efficiency of the process (also called as cold gas efficiency) is described by the ratio of the LHV of cold gas to the LHV of the waste treated, incremented by the added energy (electric or fuel) for allothermal processes per kg of waste;

$$n = \frac{LHV\ of\ \ cold\ \ gas\ \left(kJN\,m^{-3}\right)\ x\ fuel\ \ gas\ production\ \ \ )Nm^3 kg^{-1})}{LHV\ of\ \ waste\ \ treated\ \ (kJ\,kg^{-1})+allot\,hermal\ \ Power\ \ (kW)/waste\ \ flow\ \ rate\ \ (kgs^{-1})} \qquad (4)$$

In plasma gasification, the source of electric energy used to generate plasma is to be considered [10].

Another study in literature [59] shows that gross electrical efficiency depends on the prime moves which are CCGT, gas engine and steam turbine and defined as the ratio of power output to the energy provided by the prime mover in equation (5) [27].

$$Electrical\ generation\ efficiency\ [\%] = \frac{Power\ \ output\ \ [MW]}{Energy\ \ input\ \ to\ prime\ \ move\,r\ \ [MW]} x100 \qquad (5)$$

Because the heat source of the plasma treatment systems is the electrical energy other than released from combustion, is so independent of the content of treated feedstock and can be regulated to select optimal conditions [18].

Because the plasma gasification is insensitive to the waste content, for plasma treatment technology, the vital unit is plasma torch. The performance characteristics, efficiency, the supply gas, power and temperature levels and electrode lifetime are some parameters of plasma torch which affect the waste treatment device [18].

Thermal efficiency of the plasmatron

Using the system parameters (electrical parameters) of a high-power AC plasmatron operated in ARTECS facility [42], losses for the cooling system and thermal efficiency are determined by the equation (6):

$$n = \frac{P-W}{P} \tag{6}$$

where P is the power in the arcs, W is the heat losses ($W=\dot{m}c(T_o$-$T_i)$), $\dot{m}$ is the mass flow rate of the water, c is the specific heat of the water, T_i and T_o are the temperatures of the inlet water and outlet water, respectively. (P-W) is the energy for the working gas heating [42, 60].

Thermal efficiency of the plasmatron in ARTECS facility which is about 75-80% is calculated using parameters in Table 3.

Table 3. Parameters of High Power Plasmatron in ARTECS Facility

No	P [kW]	n	Q [kg/s]	$\dot{m}$ [kg/s]	T_i [°C]	T_o [°C]	H [MJ/kg]
1	1101.79	0.745257	0.118	6.583	16.96	27.16	7.25
2	1011.77	0.757711	0.106	6.046	23.82	33.52	7.52
3	1037.73	0.761923	0.106	5.806	23.28	33.46	7.75
4	1128.47	0.777179	0.125	5.773	23.46	33.88	7.30

Also, enthalpy is determined in the equation (7) [60]

$$H = \frac{Pn}{Q} + H_{T_0} \tag{7}$$

Where P is power in the arcs, n is thermal efficiency of the plasma torch, Q is the working gas flow rate (kg/s) and H_{To} is the initial enthalpy of the plasma forming gas. Enthalpy (H) is about 7.5 MJ/kg. H_{To}=0.288 MJ/kg at T_{gas}=300 K.

6. ECONOMIC ANALYSIS

Especially for countries with limited space such as Japan and European countries, the cost of landfill is high [61]. Also, a tipping fee and transportation of waste to be paid is high where disposal is difficult and landfilling is subject to some regulations from the EPA (Environmental Protection Agency). The economics of plasma gasification facility is very appropriate via multiple income streams although it is complex. Firstly, tipping fees for taking waste is removed with plasma gasification and electricity is produced for output. Also, another revenue from plasma gasification are the valuable products which are liquid fuels, hydrogen and effective syngas. There are another minor revenue streams which are slag and sulfur for sale [16].

Another cost estimation of a typical plant is given as a feedstock of 3000 tons of MSW per day with cost over 400 million $ producing about 120 MW of electricity. Also, another estimation is given for a 2000 tons MSW per day is about 250 million $ with the potential to generate 900 kWh for each ton of MSW and 1200 kWh/ton if it is equipped with cogeneration auxiliaries [62].

In literature, some different cost estimates are present in different countries. An estimation of the construction cost of a 750 TPD is 150 million US $ which equals to 0.2 million US$/TPD [16]. In Korea, 0.39 million US$/TPD is paid for 10 TPD plant constructed. According to a study [3] when the treatment capacity is increased, thermal plasma gasification processes are more economical due to decrease of construction cost with increased capacity, profits from the utilization of syngas as an energy source, and the decrease of total operation costs such as labors cost and overhead charges. When the characteristics between 10 and 100 TPD thermal plasma plants for MSW treatment is compared, thermal plasma consumption power is 0.817 MWh/ton and 0.447 MWh/ton, heat loss from waste product of masses is 16% and 10%, heat loss through system walls 14% and 7% in 10 TPD scale and 100 TPD scale, respectively. Also, energy recycling is not used in 10 TPD, whereas is used through steam turbine in 100 TPD scale [3].

Another economic analysis [63] made an estimation finding the plasma very competitive in waste treatment that the cost of landfill burial 105-160 Euros/tonne, traditional incineration 100-140 Euros/tonne, pyrolysis/thermolysis 90-150 Euros/tonnes and plasma methods 70-90 Euros/tonne and without syngas utilization 100-120 Euros/tonne [18].

So, we may come across the plasma assisted coal or waste gasification or burning as viable or not economic in some articles [3, 10, 18] while mentioning superiority of the plasma technology application compared to classical methods for this process in these articles.

7. CONCLUSION

Due to its advantages in mostly efficiency and environmental aspects, plasma technology has been preferred in energy production from waste, coal and biomass throughout the world. Plasma with high enthalpy, high temperature, high density, high residence time and reactive species such as atomic oxygen and hydrogen or hydroxyl radicals increases the efficiency of conversion reactions compared to classical systems. In the term of heat balance, gas heating value output is highly bigger than the electricity input of plasma system.

Also, plasma technology is an environment friendly technology reducing the emissions of hazardous gases such as CO, CH_4 and higher hydrocarbons, NO_x and SO_x. In plasma gasification process, because of the less tar content in syngas, electrical efficiency is higher than that of conventional one.

It is seen in literature that different types of plasma torches are used by different companies in different countries. In comparison of DC, AC and RF plasma technologies, AC plasma torches are considered as favorable especially in megawatt levels with high electrode lifetime, not requiring complicated rectifiers and lower cost. For that reason, many research programs on AC type plasma system development and new applications, like gasification of wastes and coal have been started [53, 51].

Plasma gasification technology of waste has many opportunities such as reducing the need for landfills, environmental friendly disposal of hazardous waste. Also, syngas which is final product of gasification can be used as renewable fuel or precursor of many different chemicals. On the other hand, plasma technology has some technical drawbacks which need to be improved such as extending life of the electrodes and stabilization of plasma.

In economic aspects, although different studies exist in literature, typically the installed cost of a plasma gasification plant is between 0.13-0.39 million US$/TPD (ton per day). When the treatment capacity is increased with higher TPD scale, plasma gasification processes will become more economical, means near 0,13 million US$/TPD [3]. Also, for countries with high tipping fees for MSW and high electric rates, plasma gasification plants can be considered as more economic [62]. The economic efficiency will come from increase of chemical efficiency.

In comparison of chemical efficiency between plasma technology and conventional systems; cold gas efficiency (energy efficiency) and the net electrical efficiency of the overall process are principal factors. Plasma is relatively insensitive to the waste content, so it can be used for gasification of all type of wastes with high efficiency. Also, because the tar content in syngas of plasma gasification is lower than that of conventional systems, the net electrical efficiency of the overall process of plasma gasification systems is higher than the classical ones. Apart from the efficiency of chemical reaction from the plasma effect, another crucial factor is the thermal efficiency of the plasmatron itself. Because the cost of electrical energy is considered as a restrictor factor in this technology, the crucial unit is the plasma torch performance and efficiency [18]. In this point, the efficiency of plasmatron in ARTECS Facility which is %75-80 is in considerable levels. Although the technology readiness level of the plasma technologies has a level of maturity (over 6), the application on the different type of waste management or plasma assisted coal burning/gasification needs some additional R&D activities especially in simulation and modelling for obtaining optimum conditions, process development and control of gasification or burning process. In this respect, AR&TeCS has started to develop a remote sensing, measurement and control system for hazardous process like plasma gasification and burning with KOSGEB (Ankara, Turkey), applied Horizon 2020 (European Union) program for a plasma waste gasification project, and two coal related project to TUBİTAK for low quality lignite gasification and burning.

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