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Review on the Need of a More Efficient Three-Phase ACPlasma Combustion/GasificationSystem for All Solid Waste Including Hazardous and Biomass

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ABSTRACT
Population growth, rising standard of living, urbanization, diversification of consumption materials cause increasing of waste materials and energy consumption. In the world, thousands of wastes occur every day, and most of these wastes come from solid wastes such as household, industry, agriculture, municipal wastes, etc. This increase in solid wastes is one of the most important environmental problems in the world. Conversion of these wastes into energy during the disposal process is significant importance in terms of prevention of environmental pollution, public health, and renewable, sustainable energy. Landfilling which is the simplest waste treatment method currently appears as the less preferable method for following reasons: first, the lack of land available, especially in the most populated regions. Second, landfilling causes the production of powerful hazardous gases and chemicals that can contaminate the soil and water, posing a risk to the public health and the environment. Also, other thermal methods such as incineration,gasification, and pyrolysis have been developed in order to obtain steam or electric energy by means of disposing of the biomass and solid wastes. However, these methods need to use of additional burners working with natural gas and heavy fuel. This leads to increase the cost of biomass and solid wastes combustion/gasification and additional damage to the environment. Additionally, the regulations on the protection of the environment are getting stricter. However, meeting these requirements with existing technologies will not be possible soon. In near future, combustion/gasification assisted with plasma systems for solid waste and also for coal seem to be the most promising technologies. These systems are preferred because of not only to obtain high energy efficiency but also not to create environmental problems destroying all types of wastes including toxic and hazardous structures. This paper covers existing systems especially based on plasma systems emphasizing advantages and disadvantages and how to make these systems more efficient and economically advantageous for waste to energy application. This paper, also, covers in more detail a literature review of three-phase AC plasma torches to be used for waste gasification which have been developed in France and Russia for many years and installed at our facility (AR&TeCS) in Turkey newly.
Keywords: Plasma, AC Plasma Torches, Biomass, Solid Wastes, Waste-to-Energy, Combustion, Gasification.

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I. INTRODUCTION

In Europe , people use 16 tons of material per person per year and 6 tons of waste is generated from them and 500 million people throw half a ton of household garbage away every year approximately. Also,~360 million tons of waste per year is produced from manufacturing and~ 900 million tons of waste per year from construction [1]. Plasma as the forth state of matter can be effectively adjusted in the treatment of different wastes such as municipal solid wastes, heavy oil, used car tires and medical wastes. Thus, it is considered to be an extremely attractive way of processing of waste-to-energy [2].The increase in energy efficiency is the most significant solutions of sustainable energy. Thus, the energy production from biomass and solid wastes with increasing of fossil fuel depletion and global warming is an important issue for the future society and environment. It is considered that primary energy consumption will reach 22.6 Gtep[1]in 2050 and at the same time the share of electricity will rise from 34 % to 42.5 % [3]. Therefore, recently, there are increasing demands for biomass and solid wastes combustion/gasification assisted with plasma technologies in the world to obtain energy especially electricity with more efficient and ecologic way. The plasma systems for combustion/gasification of biomass and solid wastes processes have many advantages and unique aspects in terms of technical, environmental and economic perspectives. Firstly, high temperature and high enthalpy provide efficient gasification compared to other thermal methods. Secondly,reactive species such as atomic oxygen, hydrogen, or hydroxyl radicals produced by the plasma increase the efficiency of chemical reaction relative to other conventional methods by allowing all structures including the tar to decompose.Thirdly, the rates of harmful emissions such as CO_2, CH_4, SOx, NOx can be reduced by plasma. Fourthly, due to the high temperatures of plasma technology, there are no occurrence of dioxin and furan groups which are the most important environmental problems to human health of waste incineration technologies.Furthermore, landfilling which is the least sustainable and conventional method needs to use large amount of land. However, this method has negative effects because of gas emissions such as carbon dioxide and methane from the anaerobic decomposition of the waste and also, it requires long distance transportation [4]. In plasma system, energy is produced without the need to discharge solid wastes and garbage collection areas for landfilling; so, it is economically and ecologically more advantageous. Because of these benefits and properties, the plasma assisted combustion/gasification is promising and attractive in terms of low carbon electricity production thanks to thelarge-scale deployment of renewable energy.

Thermal plasmas can be acquired by AC, DC, radio frequency (RF) or MicroWave (MW) plasmas. Although RF or MW plasmas don't have electrode erosion, they have low energy efficiency (about 40 – 70%) [5]. Most of the combustion/gasification assisted with plasma technologies today are based on DC plasma torches. However, DC plasma torches suffer from a certain number of weaknesses and drawbacks. With the objective to go over these weaknesses and drawbacks, three-phase AC plasma technology to be integrated into combustion and gasification systems has been worked for many years.Some of the advantages and features of AC plasma torches compared with DC plasma torches are given as follows. The power is stabilized and regulated by the reactors accordance with the desired stabilization value of the plasma in AC arc plasmatrons. This system simplifies the electrical circuitry and diminishes the cost since it removes the need for direct current suppliers, including rectifiers[6]. DC source units are quite complex, space-consuming and costly especially for the powers of the Megawatt range. For AC plasma torches, special DC power supply devices are not required and they can be operated using three-phase electric power from the city grid line. Moreover, the cathode lifetime at AC arc plasmatron at least two times higher than in DC ones since anode and cathodes change continuously in alternating current [7].Thus, AC plasma torches have more advantageous than DC ones so the future application of plasma will shift AC type plasma systems.

II. DEVELOPMENT OF THREE-PHASE AC TECHNOLOGIES

Three-phase AC plasma systemshave been developed in USA, Norway, France, Russia, Germany, Japan and Turkey for about 50 years and their R&D activities are given in Table 1[8]. Three-phase AC plasma systemsfor the combustion/gasification processes which have been developed by the most active research groups on multi-phase AC plasma systems in West and East are examined in this paper. The three-phase AC plasma technologies in France and Russia are focused because their density of works in this area is more than other countries.

[1]Gtep: gigatonne equivalent of petroleum (billion tep), which equates (based on lower heating value – LHV) at 11 600 billion kWh or 41.8 EJ (exajoules)

Table 1. *Three-phase AC R&D activities.*

Country	***Group / Company***	***Application Field***	***Plasma Gas***	***References***
USA	Geister, Phillips and Nicholls' team at the Aircraft Propulsion Laboratory, and the Department of Aeronautical and Astronautical Engineering (University of Michigan at Ann Arbor)	Development of hypersonic flights at Mach numbers above 7, 8 for ballistic missiles and high temperature re-entry applications	Air	[9-12]
Norway	Professor Bakken's team of the Department of Metallurgy at the Norwegian University of Sciences and Technology (Trondheim Norway)	Submerged arc furnaces for the production of ferrosilicon and silicon metal	Ar, SiO, CO	[13-27]
France	Bonet, Delmas, Foex, Gold, Badie Flamant PROMES-CNRS Odeillo	Treatment of refractory materials	Air, Ar, H, O, N_2	[28]
France	CNRS Odeillo, the Limoges University and the French Lafarge cement company	Raw cement powder decarbonization	Air, N_2, Ar, CO_2	[3]
France	the French engineering company and the French utility company (BERTIN & CIE)	A hybrid 500 kW electro-burner prototype	CH_4	[29,30]
France	Fulcheri, Fabry, Ravary, Deme, Rehmet, Takali, Gonzalez – Aguliar, Gruenberger, Probst, Grivei PROMES-CNRS Odeillo and PERSEE MINES-ParisTech	- Hydrocarbon cracking for the co-synthesis of carbon black and hydrogen - Synthesis of fullerenes and carbon nanotubes - Gasification and combustion of LHVF & Biomass	Air, Ar, He, N_2, CO	[31-47]
Russia	Rutberg's group of the Institute for Electrophysics and Electric Power at the Russian Academy of Sciences in St Petersburg (IEEP RAS)	Gasification (plastic, biomass) and hazardous and toxic waste treatment	N_2, H_2, Inert Gases, Steam, Air	[32-54]
Russia	Keldysh Research Center (KeRC)	- Gas dynamics - High temperature thermophysics - Basalt wool production - Coal gasification	Air	[55]
Germany	Neuschutz Rossner, Bebber RWTH, Aachen	Arc furnaces	Ar, Air	[56-58]
Japan	Tanaka, Tsuruoka, Liu, Matsuura Tokyo Inst of Technology	Glass melting	Ar, Air	[59,60]
Turkey	AR&TeCS (ARTECS Anadolu R&D Technology Engineering and Consultancy Company, Ankara University Technopolis)	- Plasma simulation - Development of plasma propulsion system for satellite - Material testing - Waste, Coal gasification	Air	[7] [61-63]

2.1. France

At the CNRS-Odeillo, for the high-temperature treatment of refractory materials (generally pure silica), a three-phase AC plasma system was developed in 1973 [28].In tests, different neutral, oxidant or reducing plasma gases such as air, argon, hydrogen, oxygen, and nitrogen was used. These studies showed that using air as plasma gas has a positive effect on electrode erosion and plasma stability [8].

Between 1979 and 1980, the CNRS-Odeillo, the Limoges University and the French Lafarge cement company worked a research program which is about raw cement powder decarbonization based on the Odeillo's three-phase AC technology. However, because of economic reasons, the concept was not developed [3].

In 1986, a hybrid 500 kW electro-burner prototype which is the controlled thermochemical activation of the combustion by using plasma was developed by the French engineering company and the French utility company(BERTIN & CIE) [29, 30]. This technology is based on Odeillo's technology with using graphite electrodes instead of copper and tungsten. Although this technology had major technological accomplishments such as electrode erosion issue, it was abandoned due to economic reasons.

In 1993, the development of three-phase AC technology continued in collaboration between PROMES-CNRS Odeillo and PERSEE MINES-ParisTech and the hydrocarbon cracking for the co-synthesis of carbon black and hydrogen was studied [32-35]. Between 1997 and 2003, in the field of synthesis of fullerenes and carbon nanotubes with the three-phase AC technology developed [36,37].

In 2002, the 250 kW three-phase AC technology was established firstly at PROMES-CNRS Odeillo was located, and then it was moved to PERSEE-MINES ParisTech Sophia Antipolis. Since 2009, PERSEE-MINES ParisTech has been studied the three-phase AC plasma system with gasification and assisted combustion [8].

Many wastes and biomass sources are consisted of poor low heating value organic matter. A plasma assisted combustion of low heating value biomass with the three-phase AC plasma torch working with consumable graphite electrodes and operating with air at 100 kWe has been developed at PERSEE MINES ParisTech and PSL-Research University [64]. In Figure 1, the experimental setup which includes the three-phase AC plasma torch, the combustion chamber, the biomass feeding injector, the power source, the cooling and the measurement system is shown. The electrodes' material is graphite for the possibility of continuous feeding. The air with a flow rate of 55 Nm^3/h is used as plasma gas. In order to reduce heat losses due to radiation, a ceramic shield is placed inside the torch. Also, efficiency increases by this way. The frequency is set at 80 Hz accordance with the characteristics of the power supply and a 263 kW three-phase converter was used in this study. The current can be set between 150 A and 400 A. The diameter of electrode is 25 mm, which allows this amperage to be not harmful. The angle between the electrodes an important parameter in terms of distance and resistance of the arc column and obtaining high power. Thus, electrodes have 20^o to the main axis in this study. For the same current value, this leads to the arc column a longer distance and higher resistance and so providing higher power from the source.

Figure 1.*Three-phase AC plasma torch and combustion chamber [64].*

In experiments, wood ships were used as a test sample. The characteristics of the tested biomass such as its heating values, water content, percentages of sulfur, hydrogen and ash are given inFigure 2and

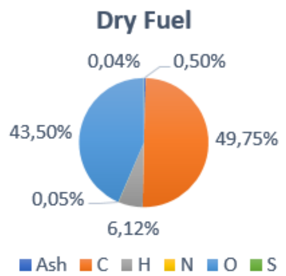

Figure 2.*Characteristics of the tested wood ships [64].*

Table **2**. The measurement setup is composed of a gas chromatograph and a Non-Dispersive InfraRed (NDIR) sensor, an oscilloscope with thermocouples and a high-speed camera.

Table 2.*Characteristics of the tested biomass [64].*

Raw Fuel	
Moisture (%)	5
Ash content (%)	0.29
Net Heating value (MJ/kg)	20.51
Density (kg/m^3)	300
Ash softening point (^oC)	1150

The combustion test was performed in five steps: heating phase without combustioninjection of 1.1 kg/h, then 2.2 kg/h and then 3.3 kg/h. Finally, with a rapid stop combustion test was completed. The first four steps last each 15 minutes. According to the test results, it is considered that the results of

NDIR sensor are more reliable. The average power supplied by combustion equals to 5.62 kW/kg which is close to level that the total combustion will produce. Also, it is considered that through gas emissions the combustion efficiency exceeds 95%. CO emissions have been neglected while analysis of burning gases has been carried out. However, CO_2 and H_2 emissions are consistent with power measurement and the feeding rate.

As a result, the Center PERSEE MINES-ParisTech has been working for many years to develop 3-phase AC plasma technology. Its aim is to deal with the limits of DC plasma torches and reduce OPEX (operational costs) and CAPEX (capital costs)for the plasma based systems[3].

2.2. Russia

In the field of gasification and waste treatment, research and development studies on the three-phase AC technology has been carried out by Rutberg’s group of the Institute for Electrophysics and Electric Power at the Russian Academy of Sciences in St Petersburg (IEEP RAS).

The authors [50] focused on two types of stationary multiphase AC plasma generators (low-temperature plasma generators) to develop waste destruction and processing. There are two different arc burning modes: a contracted mode and a diffuse mode. While at contracted mode the electron concentration n_e is $\geq 10^{16}$ cm^{-3} and temperature T is $\geq 10^4$ K in the discharge zone, at diffuse mode $n_e \sim 10^{14} – 10^{15}$ cm^{-3} and T ~(5-7) × 10^3 K. In Table 3, the plasma generators of average power (up to 50 kW) and high power (up to 500 kW) working on oxidizing media and other parameters such as flow rate, thermal efficiency and electrode lifetime are given in the discharge chamber of a multiphase low-temperature (thermal) plasma generator.

Table 3. *The plasma generators of average power (up to 50 kW) and high power (up to 500 kW) working on oxidizing media and other parameters in the discharge chamber of a multiphase low-temperature (thermal) plasma generator [50].*

	High Power	**Average Power**
Power (kW)	100 – 500	up to 50
Flow Rate (g/s)	10 – 70	2 – 25
Thermal Efficiency	70 – 90 %	80 – 95 %
Electrode Lifetime (h)	over 100	100

In the article “*Novel Three-Phase Steam-Air Plasma Torch for Gasification of High-Caloric Waste”,* authors have developeda three-phase high-voltage plasma torchworking on steam and its mixtures with air for plastic waste gasification [54]. The three-phase air-steam plasma torch schematic diagram is given in

. InTable 4, the arc parameters obtained during the experiments are given.

For the utilization of plasma technologies such as syngas production, controlling of the working gas heat content in a wide range at the outlet is important and the multiphase plasma generators allow this phenomenon. When air is used as a working gas (25 – 70 g/s), the three-phase plasma torch can provide an energy input around 1.5 – 12.5 MJ/kg. This allows a long-life time of continuous operation of more than a hundred hours.

Figure 3represents the diagram of multiphase single chamber. The electrodes from fusible materials such as copper and materials based on copper, like “Cu + Fe” are used instead of tungsten-based alloys which areunable to work in oxidizing media. In Figure 4, the three-phase AC plasma torch of average power (30 kW) which is high voltage plasma torch with rod electrodes positioned in cylindrical channels is shown.

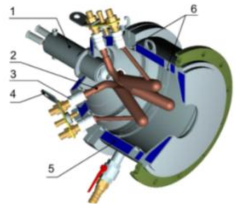

Figure 3.*Diagram of the three-phase AC plasma torch: 1 - injector; 2 - electrode; 3 - insulator; 4 - terminal; 5 - cooling jacket; 6 - loop of working gas supply [50].*

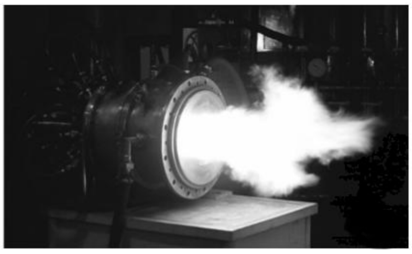

Figure 4.*The photograph of the three-phase AC plasma torch of average power: power 30 kW, working gas – air [50].*

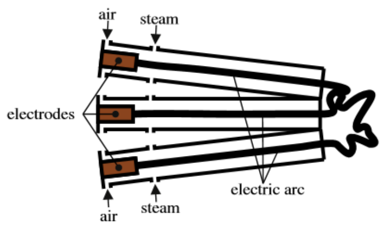

Figure 5. The schematic diagram of the three-phase air-steam plasma torch [54].

Table 4.*The arc parameters [54].*

Voltage drop (kV)	1.0 – 1.8
Current (A)	28.5
Power (kW)	52 – 86
Thermal Efficiency	94 – 95 %
Steam Flow Rate (g/s)	3.7
Air Flow Rate (g/s)	~1
Average Discharge Length (mm)	798
Average Arc Diameter (mm)	4.47
Arc Temperature (K)	10000 - 11500
Electrode Lifetime (h)	No less than 300 - 350

Another study in Russia presented experimental results of wood, coal and refuse derived fuel (RDF) air plasma gasification [52].The experimental plant which has been constructed for investigations of the plasma gasification processes of these materials is shown in Figure 6and the experimental installation is described more detailed in [65].

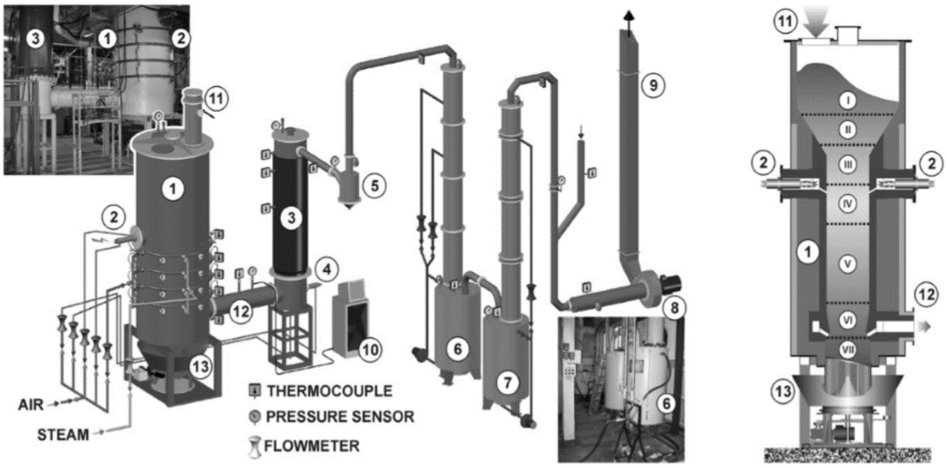

Figure 6. *General view and principal scheme of the experimental plant for plasma gasification of wastes: 1 – reactor gasifier; 2 – plasma generator; 3 – afterburner; 4 – duty torch; 5 – cyclone; 6 – spray scrubber; 7 – nozzle scrubber; 8 – exhaust fan; 9 – outlet pipe; 10 – gas analytic equipment; 11 – feeding system; 12 – syngas output pipe; 13 – device for slag quenching and discharge. I – accumulation; II – evaporation; III – pyrolysis; IV – active exothermal reactions; V – reduction; VI – weak reactions; VII – slag removing [65].*

The three-phase torch with rod electrodes which supplies power up to 75 kW has been successfully performed by a source of 6 kV and 10 kV and up to 30 A arc current. The experiment resultsin terms of temperature, flow rate, yield etc. for coal, wood and RDF are showed in Table 5. Also, the composition of the product gas for coal, wood and RDF are given in Figure 7.

Table 5.*Experimental results of plasma gasification of coal, wood and RDF [52].*

Experimental Results	***Value for coal***	***Value for wood***	***Value for RDF***
Average temperature in the reduction zone on the wall (K)	1127.15	1311.15	1149.52
Average temperature in the reduction zone on the axis (K)	1383.15	1723.15	1413.15
Temperature of the product gas at the reactor outlet (K)	795.65	1171.15	1175.25
Total electrical power consumed by the plasma generators (kW)	58.68	79.05	42.73
Flow rate of air blow (g/s)	21.16	42.42	43.33
Flow rate of steam blow (g/s)	1.70	-	-
Plant productivity on fuel (g/s)	9.31	31.86	30.55
Specific output on gas (m^3/kg)	3.41	2.46	1.98
Yield of the product gas (g/s)	30.92	75.19	64.78
Density of the product gas (kg/m^3)	0.97	0.96	1.07
Product gas LHV (MJ/kg)	4.81	6.16	6.18

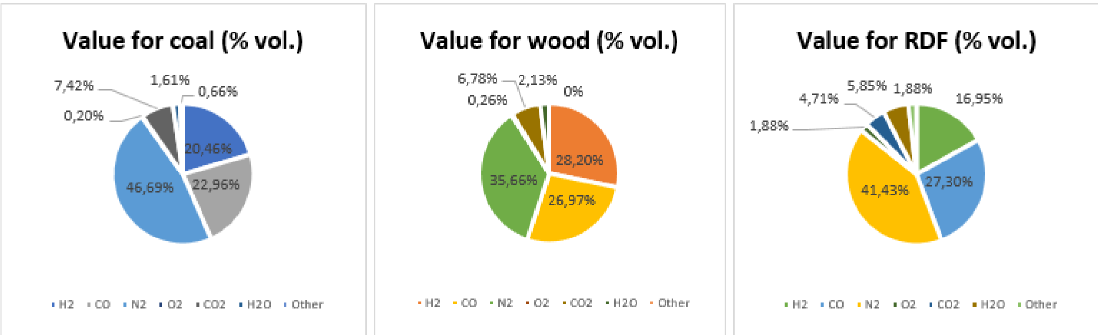

Figure 7.*The composition of the product gas for coal, wood and RDF [52].*

The erosion of the rod electrodes goes up when the power is increased by increasing the current. In order to deal with erosion of electrodes, the powerful high voltage three-phase AC plasma torch with hollow electrodes was created instead of rod electrodes [52]. The operational characteristics of this plasma torch are given in Table 6. The arc current depending on the air flow rate is ~ 85 A and the thermal efficiency of the plasma torch is ~ 92 %. The studies show that the plasma torch can run continuously for 2000 h.

Table 6.*Operational characteristics of powerful three-phase AC plasma torch [52].*

Air flow rate (g/s)	***Voltage drop (RMS) (V)***	***Power (kW)***	***Enthalpy (MJ/kg)***	***Average temperature (K)***
68	2200	330	5.09	3400
86	2450	360	4.44	3250
108	2700	390	3.89	2900
115	2800	400	3.75	2850
122	2850	410	3.63	2800

2.3. AR&TeCS (Turkey)

In Turkey, the establishment of the Three-Phase AC High-Power Plasmatron Test System at AR&TeCS (ARTECS Anadolu R&D Technology Engineering and Consultancy Company, Ankara University Technopolis) facilities has been successfully completed and the qualification tests have been carried out with Keldysh Research Center

(KeRC, Moscow) cooperation as well.Because of the superior features and advantages, AC technology which is the new system in recent times has been chosen at AR&TeCS facility.Figure 8shows a conceptual sketch of a complete plasmatron test system, established a similar one in the AR&TeCS facility. The plasmatron relates to gas arc heaters of megawatt class and the working gas is air. The plasmatron system is decomposed into five subsystems which are electrical subsystem, cooling subsystem, gas feeding subsystem, ventilation subsystem and data acquisition (DAQ) and control subsystem [7]. Also, an image of a 1-MW plasmatron test systemdesigned at the KeRC is shown in Figure 9.

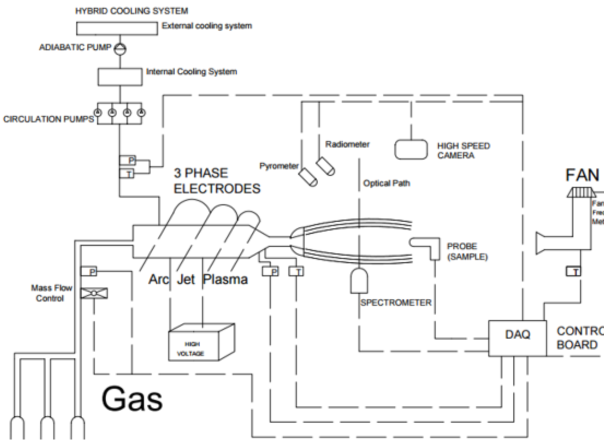

Figure 8.*A conceptual sketch of a complete plasma torch test system [7].*

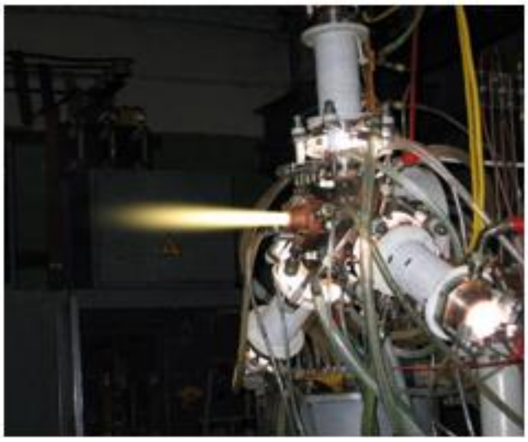

Figure 9.*An image of arc jet plasma generator.*

At an operation with air as a working gas, the maximum characteristics, electrode lifetime and thermal efficiency parameters are given in Table 7[7].

Table 7.*The maximum values obtained during tests, electrode lifetime and thermal efficiency.*

Average Arc Voltage (V)	1065
Average Arc Current (A)	325
Power (kW)	1040
Gas Flow Rate (g/s)	104
Chamber Temperature (K)	4460
Thermal Efficiency	75 – 80 %
Electrode Lifetime (h)	No less than 500

The plasmatron test system available at ARTECS; due to high power and AC technology, is suitable for disposing of all solid waste including hazardous and biomass by combustion/gasification.Figure 10shows the schematic illustration of ARTECS's plasma waste-to-energy concept. The system to be developed is divided in two parts: the first one is the main plasma torch system, which is an electro-thermal device producing a high-temperature plasma flow by converting electric power into thermal power. The second part of the system is the integration of plasma torch to waste gasification reactor (an oxygen-starve environment) to convert waste into high-energy syngas and valuable slag.

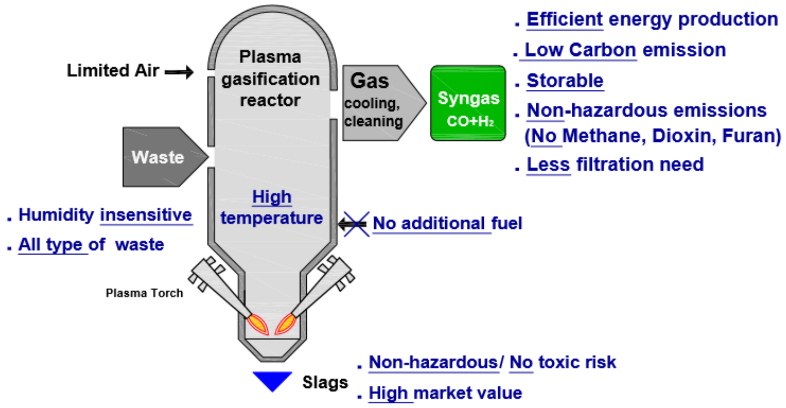

Figure 10.*The schematic illustration of ARTECS's plasma waste to energy concept.*

The benefits from waste-to-energy system which will be developed by ARTECS are given inTable 8.

Table 8.*The needs and benefits.*

Needs	Benefits from using ARTECS's system
Reduction of landfilling	Landfilling will not be needed, which implies transport and operational costs and consumes huge spaces, besides causing permanent pollution to the surrounding soil and groundwater. This system reduces the volume of waste by 90%, while the remaining amount is transformed in construction materials.
Flexible, adaptable and easy to use solution for the waste management	Automation, user friendly control and intervention systems via LabVIEW application make system easy to use. Thanks to its modular and scalable structure and flexible adaptation, can be used for different size of waste and different application.
Destruction of hazardous wastes without further expensive treatments	Thanks to its ability to rich high temperatures (5000 ^{o}C) and its active radicals, the system provides an environmentally friendly, efficient, safe and low-cost method for the energy efficient disposal of all types of wastes, including medical, radioactive and industrial complex wastes., without any preliminary transformation process. Also, the hazardous emissions like furan, dioxin, tar, CO_2, CH_4, SO_x and NO_x will be reduced.
Valuable market products from waste	This technology realizes the production of saleable products from wastes. It aims to convert organic molecules of waste into syngas, to be used for the generation of electricity and to produce many other chemical compounds, applicable in various industrial sectors. Inorganic compounds are transformed into glassy slag, which could be sold in the construction industry.
Local energy production from sustainable sources	Municipalities will meet their energy need locally from their own local waste. If energy not needed, syngas, output of waste gasification can be stored safely like natural gas, until it is needed.

III. CONCLUSION

The increase in wastes is one of the most important environmental problems in the world. Among environmentally friendly and sustainable solutions for this environmental problem, plasma technology is among the most appropriate method for waste disposal. Today, combustion/gasification with plasma technology has been preferred for the processing of all solid wastes and biomass in the world because of its advantages such as energy development efficiency and environmentally friendly effects. Due to high temperature, high enthalpy, high energy density, high residence time and reactive species such as atomic oxygen and hydrogen or hydroxyl radicals, the efficiency of conversion reactions increases. Also, the emissions of hazardous gases such as CO, CH_4, SO_x, NO_x can be reduced by the plasma, so this is an additional advantage for the use of plasma.

Existing arc plasma systems are DC and AC plasma torches. AC plasma torches have significant advantages mentioned below.

- For the power of the Megawatt range, the DC source units are quite complex, space-consuming and costly. For AC arc plasmatrons, special power supply devices are not required but they can be operated in an industrial three-phase electric power line. In addition to the absence of power cap, the switching equipment on the line is simple and reliable.

- In DC arc plasmatrons, the cathode lifetime is much lower than in AC ones. In the AC arc plasmatron, the cathode and the anode are replaced by the network frequency. This makes the cathode lifetime at AC arc plasmatron at least two times higher than in DC ones.
- In the DC arc plasmatron, ballast resistors are provided for supply stability for arc stability. However, this causes active power losses. In AC arc plasmatrons, reactors are connected in series to provide arc stability.
- In AC plasma torches, different water-cooled or consumable electrode materials can be used such as, copper, materials based on copper (Cu + Fe), tungsten, graphite, aluminum and molybdenum.

Nowadays, AC plasma torches instead of DC ones are considered as highlyattractive technologies in several large-scale high-power industrial applications such as waste treatment by combustion/gasification. This paper showed a literature review of three-phase AC plasma torches which have been improved in France, Russia and installed at ARTECS (Turkey). Comparison table of three-phase AC plasma technologies is given in detail in

Table 9. When into consideration of specifications of plasma torches in Table 9,the high-power three-phase AC plasma technology which is available at AR&TeCS facility is superior to current plasma solutions and it is anappropriate technology for plasma-assisted combustion/gasification.

Table 9. Comparison of three-phase AC plasma technologies.

Companies:	**MINES Paristech (France)**	**IEE RAS (Russia)**	**AR&TeCS (Turkey)**
Types of Plasma Technology	Three-Phase AC	Three-Phase AC	Three-Phase AC
Working Gas	Air	Air – Steam [54]	Air
Power (kW)	100 [64]	52 - 86 [54]	1040
Material of electrodes	Graphite [64]	Copper and materials based on copper (Cu + Fe) [50]	Copper
Electrode Lifetime (> 400h)	X	X (No less than 300 - 350 [54])	✓ (No less than 500)
Thermal Efficiency (> %70)	✓	✓	✓
Temperature (> 3700^{o}C)	✓	✓	✓

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