Use of plasma technology in power engineering

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Abstract:
The paper describes the principle and physical phenomena in plasma generators that are used in material technology for spraying and refinement thin surface layers. The paper especially deals with applications plasma generators in power engineering where are using, for starting and stabilizing combustion of coal in a power plant and for ecological treatment of communal waste and biomass gasification. Arc models and basic problems of plasma are discussed. Plasma generators are discussed from the point of the view of their design and working process.

INTRODUCTION

The paper is survey of principles and technology and part of basics theory with use of published introduces and references.

Plasma generators (torches or electric gas heaters) are used extensively in scientific investigations, in technology and processing. Plasma is used in highly efficient processes in plasma chemistry and plasma metallurgy. A powerful impetus to the development of electric arc plasma torches has been provided by rocket technology.

Development of efficient plasma torches required extensive scientific investigations in the area of high-temperature dynamics and electro physics, examination of the working process in the plasma torch, especially the interaction of the electric arc with the gas flow, and search for new circuits and technical solution.

1 PLASMA GENERATOR – TYPE AND DESING

With use references [1]

1.1 Principle of heating gas in plasma torch

The plasma generators consist of three essential elements. Two mutually insulated copper electrodes cathode and anode which comprising discharge chamber. Heating of a gas or a steam in plasma generators takes place as a result of interaction with the arc. The efficiency of heating strongly depends on the method of organizing this interaction. The optimum working process should satisfy two requirements. Firstly, it is evident to obtain the maximum mean mass temperature a large part of the heated gas should interact with the arc discharge. Secondly it is necessary to ensure thermal regime off all sections of the plasma generators in which the operating life of the device would be sufficiently long.

Arc plasma generators can be generally divided into two classes, transferred arc torches and non-transferred arc torches. In transferred arc torches the arc is established between the electrode inside the torch and the material to be processed. Their main advantage is high heat flux to the material due to the high power density in the considered electrode region of the arc. Transferred arc torches have been developed for use in the metallurgical industry.

Arc discharges are inherently unstable. The principal goal of the design of arc generators is stabilization of the position and parameters of the arc and to obtain plasma properties needed for a specific application.

According to the type of stabilization, the plasma generators systems may be divided into three groups:

1) Plasma generators with vortex arc stabilization
2) Plasma generators with magnetic arc stabil.
3) Plasma generators with stabilization of the arc by the channel walls

An additional classification of arc torches can be made according to the mechanism of cathode emission. For graphite and refractory metals like tungsten the electrons are emitted by thermo ionic emission (hot cathodes). The cathodes are usually rod shaped. Thoriated tungsten is a typical material used for its high electron emission ability and low erosion rate in non-oxidizing gases. Graphite electrodes exhibit a very high erosion rate and are used mostly as consumable moving cathodes. A graphite cathode is used in the water stabilized torch.

For cathodes of materials with lower melting temperature like Cu, thermally enhanced field emission is more typical. The electrons are emitted due to the high electric field strength on the surface of the electrode, especially on the tips of microscopic surface irregularities. As the temperature of the emitting surface is somewhat lower, cathodes of this type are called cold cathodes. The electrodes are commonly designed as hollow, usually with magnetic coils surrounding the electrode to enhance electrode spot rotation.

2 ARC MODEL AND BASIC PROBLEM OF PLASMA

With use references [2], [3]

2.1 Basic properties of thermal plasma

Thermal plasma are characterized by high temperature and high particle densities. These plasmas are close to Local Thermodynamic Equilibrium, i.e. all particle species can be characterized by the same temperature. As the equilibrium is maintained by collision between particles, Thermal plasma are mostly produced at higher pressures, close to or higher than atmospheric pressure. The plasma jets are characterized by: temperatures, velocities, fundamental or excited state densities, as well as the in-flight particles in plasma or during their flattening and the resulting splat cooling.

The Local thermodynamic Equilibrium assumption is based on the following general conditions:

- the dominant ionisation process is given by electron – ion, atom collision: the densities of species in the plasma obey Saha equation

- the dominant excitation process is also given by electron – ion, atom collision: the species follow a Boltzmann distribution

- plasma species follow a Maxvellian distribution in temperature T_e and heavy particle temperature T_h, that is $T_e > T_h$: from kinetic energy balance equation

$$\frac{T_e - T_h}{T_e} = \frac{3\pi m_h}{32 m_e} \cdot \left(\frac{e l_e E}{\frac{3}{2} k T_e} \right)^2 = \frac{p m_k}{24 m_e} \left(\frac{e l_e E}{k T_e} \right)^2 \quad (1)$$

where l_e is the mean free path between two electron-heavy particle collision ($l_e \approx 1/p$), we have

$$\frac{T_e - T_h}{T_e} = \frac{\Delta T}{T_e} \div \left(\frac{E}{p} \right)^2 \quad (2)$$

implying that a high pressure plasma ($p \approx 1$ atm) at $T_e \approx 1$ eV is expected to have $\frac{\Delta T}{T_e} \leq 20\%$

- the velocity distribution is Maxwellian

$$f(v) = \frac{4 v^2}{\sqrt{\pi} (2kT/m)^{3/2}} e^{-mv^2/kT} \quad (3)$$

- the population densities of the excides states for each plasma species follow a Boltzmann distribution

$$\frac{n_{r,j}}{n_r} = \frac{g_{r,j}}{Z_r} e^{-E_{r,j}/kT} \quad (4)$$

where $g_{r,j}$ is the statistical weight of j-th state, n_r is the ion density of the r-th specie, $n_{r,j}$ the density of ions with excitation energy

$$E_{r,j}, Z_r = \sum_j g_{r,j} e^{-E_{r,j}/kT} \quad (5)$$

- the main ionisation process is due to electron collision and plasma species obey Saha equation

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$$\frac{n^{(s+1)}}{n^{(s)}} = \frac{2 Z^{(s+1)}}{Z^s} \frac{(2\pi m_e k T)^{3/2}}{h^3} e^{-E^{(s+1)}/kT} \quad (6)$$

where $n^{(s)}$ is number density of s-times ionised atoms, regardless of excitation states, n_e is the electron number density and

$$Z^{(s)} = \sum_j g_j^{(s)} e^{-E_j^{(s+1)}/kT} \quad (7)$$

($g_j^{(s)}$ is the statistical weight of j-th state)

The basic models (which describe arch) consist usually of a set conversation equation which describes the equilibrium at steady state: mass conservation (scalar), momentum conservation (vector), energy conservation (scalar), current conservation (scalar). The collective variables function of (r,z) in cylindrical co-ordinate system and representing the plasma are: density ρ (r,z), velocity v=[v_r(r,z), v_z(r,z)], temperature T (r,z), electric potential Φ (r,z).

2.2 Qualitative analysis of Elenbaas- Heller equation

The steady – state radial temperature distribution of the optically thin cylindrical arc is described by the energy balance equation known as the Elenbaas – Heller equation. The integral energy balance equation of cylindrical arc column can be written in the form:

$$\frac{\partial \overline{\rho v_z h A}}{\partial z} = A \overline{\sigma} E + 2\pi R \left(k \frac{\partial T}{\partial r} \right)_{r=R} - 4\pi \overline{\varepsilon_n} A \quad (8)$$

where r is plasma density, v_z axial velocity, h enthalpy, k thermal conductivity, T temperature, e_n net emission coefficient representing power loss due to radiation and E electric field intensity. $A = \pi R^2$ is the cross section of the arc chamber walls per unit length, r and z are the radial and axial coordinates.

3 USE OF PLASMA TECHNOLOGY IN POWER ENGINEERING

With use references [4]

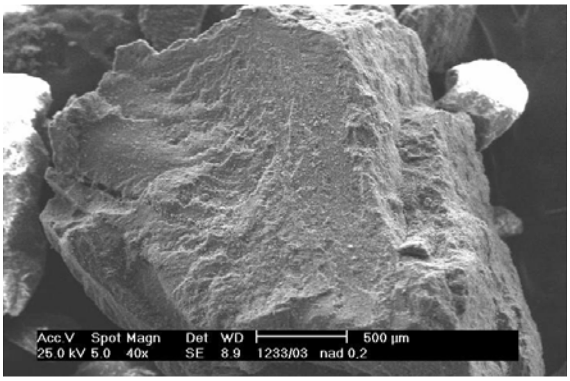
In power engineering can be use a plasma technology for starting and flame stabilization coal in boilers. So as to boiler with powdered fireplace reliably run against and started on a large scale generate pair it is necessary light coaly powder additional fuelling. Generally use mazut, natural gas and or light heating oils. These Media however go up in price production and often deteriorate environmental characteristics arrangement. Like substitute medium it is possible use plasma technology.

Implementation plasma technology non-decreasing function increased title to construction boiler. Adjustment pass through only powdery burners on which is necessary installs plasma torch. Service plasma technology isn't exacting and it is possible they fully automated with driving systems power station.

3.1 Plasma in the process of ignition of powder coal

Plasma works right on air and primary coal mixture moving in powdered burner. Temperature on entry primary mixtures is among 80- 150 °C. Plasma temperature on exit from plasma torch is among 2000–5000 °C. At contact cold air and plasma burner from whose flows ionized gas raises great thermal gradient and coal mixture is bump heated. In a zone of mutual efficiency of plasma with primary mixtures coal with medium average size 100 μm heats up at the speed of 1000- 10 000 °C/s.

It was found out experimentally, that coal particles with size to the 25 mm are break down during 0, 01- 0,05 s thermal incidence on ten fragments. This phenomenon called also like a thermal explosion particles and leads to intense growing surface in the interface fluent and solid phase and to the increased reaction possibility of coal.



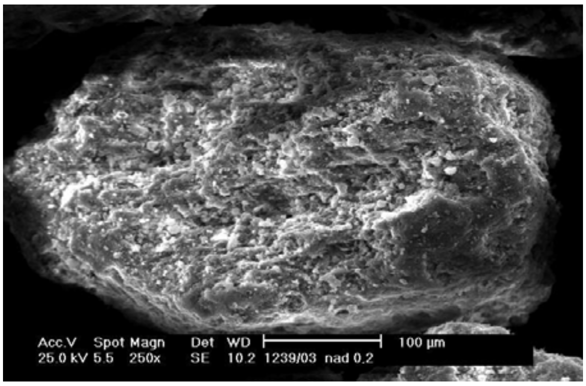


Fig.1: Coal particles before and after the contact with low-temperature plasma [4]

Thermal shock Fig. 2, 3 accelerates the release of combustible substances many times due to the significantly enlarged and disturbed surface and due to the occurrence of very fine particles. Volatile substances are released from these particles such as CO, CO2, CH4, C6H6, N2, water and nitrogen retaining compounds (pyridine C5H5N, pyrrole C4H5N).

Destruction of ash compounds and reaction of volatile substances with oxygen occurs, whilst the following elements are created in the gaseous phase: atomic forms (O, H, N, C, S), elements of mineral parts of coal (Si, Al, Ca), radicals (NH, CH, CN, OH and other), positive ions (C+, H+, N+, O+, CO+, Si+, K+ and other), negative ions (O-, H-, N-2), and further the so called electron gas occurs also in the gaseous phase. Afterwards a coke residue is heated up to the temperature of gasification and a coke residue reacts with the forming gaseous phase. With the transition of volatile substances such as CO, H2, CH4, C6H6, CO2, N2, H2O and other substances into the gaseous phase they begin to react with the air and also with each other.

The effect of low-temperature plasma is shown in intensity of reactions in the gaseous phase, by reaction with active particles, by low level of energy needed to cause a chemical reaction. It was shown that activation energy decreased already at the transition of reagents from the molecular form to atomic form.

3.2 Practical usage of plasma technology at the boiler

In the world is most often using linear type plasma torches. To generation plasma serves dry clean air (impurities decline lifetime electrodes). Power series 10- 350 kW makes it possible structure powdery burners by power 1- 35 MW. Consumption pressurized air is in range 3- 50 $g.s^{-1}$ with required operational pressure does 0,25 - 0,3 MPa. Hour consumption cooling waters is 8 kg.kW^{-1} power plasma torches.

In ČR are similar arrangements unique. This technology is tested in power station Prunerov I by firm ORGREZ Inc. It is installed on one block about power 110 MW.

3.3 Application of plasma technology at the Prunéřov Power Plant (EPR1)

The boiler at EPR1 is a bi-draught type with granulating furnace with total thermal output of 290 MW and steam output of 350 t/h. The boiler incorporates five grinding circuits with direct blowing of powder into 5 two-part burners positioned above the discharge hopper of the combustion chamber. Main burners are designed as turbulent, waste and flow burners. The crushing circuits are fitted with ventilator grinding mills. Fuel after having been pre-dried in the drier falls into the grinding mill rotor, which causes a pressure gradient for conveyance of powder mixture into the classifier and then to the fraction separator into the main and waste burner.

On powdered coal burner (on MO51) are manned as a whole two generators low - temperature plasma. . Low - temperature plasma rises in space delimited copper cathode, copper anode and insulated teflon coat, by the instrumentality of electrical discharge on vortex flow air. Air is to the plasma generators incoming in two levels. Over tree slotted tertiary vortexes lead cathode and six tertiary vortexes lead anode.

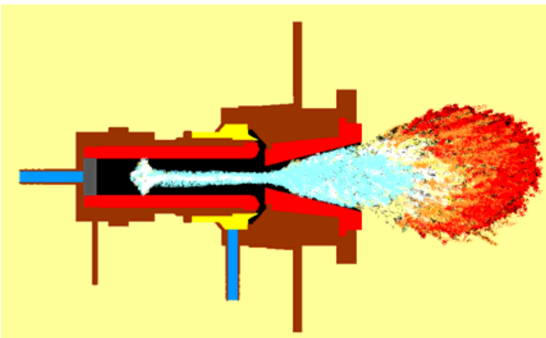


Fig.2: Chart of generator of low-temperature plasma [4]

Conditions for achievement what biggest service life cathodes and anodes electrodes is theirs intensive cooling outer cover by demineralize water. Temperature rising cooling waters would not get over ate 60°C. To extension service life cathodes and anodes electrodes in zone generation plasma it is necessary use pre dried air. Flange susceptible interface plasma torches to chamber term chemical fuel processing is in consequence high thermal gradient low - temperature plasma cooled water

4 SOLID CARBON WASTE AND BIOMASS GASIFICATION

With use references [5]

Plasma gasification technology has been demonstrated in recent studies as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilization. It is a technologically advanced and environmentally friendly process of disposing of waste and converting them to usable by-products. It is a non-incineration thermal process that uses extremely high temperatures in an oxygen starved environment to decompose completely the input waste material into very simple molecules [1]. The products of the process are a combustible gas, known as synthesis gas, and an inert vitreous material, known as slag. Furthermore, it consistently exhibits much lower environmental levels for both air emissions and slag leach ate toxicity than competing technologies, e.g. incineration.

Standard gasification technologies operate the reactor in the 400–850 °C range. They do not use any external heat source and rely on the process itself to sustain the reaction. Normal gasifiers are really “partial combustors”, and a substantial portion of the carbon is combusted just to support the reaction. Their gasification process produces a fuel gas similar to the gas produced by the plasma process, although it is much dirtier and contains char, tars and soot. The lower temperatures cannot break down all the materials. With standard gasification, many materials must be sorted out of the waste stream before reaching the reactor and land filled or processed in other ways. Because of the low temperature used, the gas that is produced by a standard gasifier has tars that are difficult to remove and other contaminants that must be further cleaned. The char residue is up to 15% of the weight of the incoming material and must still be land filled. In addition to these drawbacks, most standard gasification systems cannot feed heterogeneous waste, e.g. municipal solid waste, directly from the truck.

Plasma gasification uses an external heat source to gasify the waste, resulting in very little combustion. Almost all of the carbon is converted to fuel gas. Plasma gasification is the closest technology available to pure gasification. Because of the temperatures involved, all the tars, char and dioxins are broken down. The exit gas from the reactor is cleaner, and there is no ash at the bottom of the reactor.

4.1 Process description

The block diagram presented in Fig. 3 includes the main sections of a plasma waste treatment plant. The waste feed sub-system is used for treatment of each type of waste in order to meet the inlet requirements of the plasma furnace. For example, for a waste material with high moisture content, a drier will be required. However, a typical feed system consists of a shredder for solid waste size reduction prior to entering the plasma furnace.

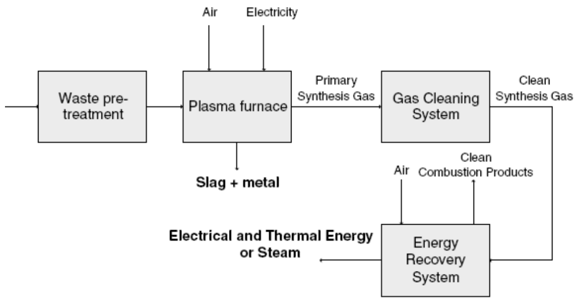


Fig.3: Main sections of a plasma waste treatment plant [5]

The plasma furnace is the central component of the system where gasification/vitrification are taking place. The gas cleaning sub-system has to achieve the elimination of acid gases (HCl, SOx), suspended particulates, heavy metals and moisture from the synthesis gas prior to entering the energy recovery system. The energy recovery system can be based on a steam cycle, gas turbine cycle or a gas engine. Depending on the quality of the produced synthesis gas, the best option can be one of the above energy recovery scenarios. In addition, alternatively, the energy recovery system can be a chemical fuel production unit, such as for hydrogen or methanol.

5 WATER STABILIZING PLASMA TORCH WSP AND HYBRID TORCH WSP-H DEVELOPING IN AV IPP CAS

With use references [6]

5.1 *Plasma generators stabilized by gas and water vortex*

Plasma jets with substantially different characteristics that cannot be achieved in gas torches are generated in arcs stabilized by a water vortex. Besides the apparent advantage of water-stabilized generators, namely, that no gas supply is needed because the plasma is produced by heating and ionizing steam evaporated from the stabilizing water vortex, there are many other differences between gas and water torches in plasma processes, plasma properties and especially in performance characteristics in plasma processing. Water torches are characterized by an extremely low plasma mass flow rates, and thus for the same arc power the plasma enthalpy is several times higher than enthalpies achieved in common gas torches. Water torches have been industrially applied especially for plasma spraying.

The physical limits of the two principles, the gas and the liquid arc stabilization, do not allow generation of plasmas with parameters in a wide region between the two principles. For some applications such as plasma spraying, where plasma jets are used to heat and accelerate the particles injected into the jet, the high enthalpy jets generated in water torches ensure a high level of efficiency of the particle heating and thus high throughputs, while low plasma flow rates and density result in lower efficiency of the particle acceleration. Thus, it is desirable to create a plasma torch with thermal characteristics typical for the water torches but with increased plasma flow rates and densities. These ideas led to the development of the hybrid water/gas torch where principles of arc stabilization by gas flow and water vortex are combined. The hybrid torch is composed of two stabilizing chambers. Plasma produced in the cathode arc chamber with the gas stabilization enters the second chamber with the water stabilization.

5.2 *Developed plasma generator*

The new-type hybrid water/argon plasma torch was derived from the water plasma torch, in which the arc was stabilized by a vortex of water. In the hybrid torch the arc chamber is divided into a short cathode part, where the arc is stabilized by a tangential gas flow with a vortex component, and a longer water-stabilized part. This arrangement not only provides additional stabilization of the cathode region and protection of the cathode tip, but also offers the possibility of controlling the plasma jet characteristics in a significantly wider range than that of pure gas- or liquid-stabilized torches. In contrast to the gas torches, the hybrid torch is equipped with an external water-cooled rotating disc anode positioned a few mm.

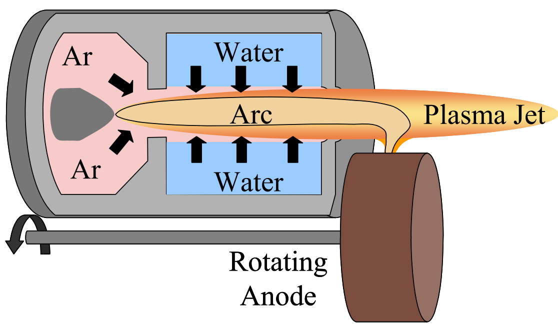


Fig.4: Char of hybrid plasma generator

Current in electric arc [A]	*300*	*400*	*500*	*600*
Input power [kW]	84	106,8	139	176
Mass flow rate[g/s]	0,204	0,272	0,285	0,325
Average temperature[K]	13750	14500	15400	16200
Temperature in the core of jet [K]	19000	23000	26200	27200
Average enthalpy [MJ/kg]	157	185	230	272
Average velocity [m/s]	1736	2635	3247	4230
Velocity in the core of jet [m/s]	2494	4407	5649	7054
Average density[kg/m^3]	4,15 x10^{-3}	3,64 x10^{-3}	3,1 x10^{-3}	2,72 x10^{-3}
Density in the core of jet[kg/m^3]	1,19 x10^{-3}	1,23 x10^{-3}	0,98 x10^{-3}	0,92 x10^{-3}
Reynolds number R_e	473	786	1140	1770
Mach number	0,317	0,445	0,505	0,617

Tab. 1: Parameters generator thermal plasma with water stabilization power arc producing in AV Prague CR

The torch affords the possibility of controlling plasma velocity and momentum flux in the plasma jet by changing the argon flow rate, almost independently of plasma temperature, which is determined by an arc current. In plasma spraying, it may be advantageous that heating and acceleration of injected powder particles be controlled independently.

Similar to water torches, the hybrid torches are characterized by high values of the arc voltage, high plasma temperatures and high plasma velocities. Thus, in plasma spraying, the torches exhibit performance characteristics typical for the water-stabilized torches, especially very high spraying rates and the ability for good melting of any sprayed material. The fields of application of the hybrid torches are thus large area coatings, powder treatment and spraying materials with high melting.

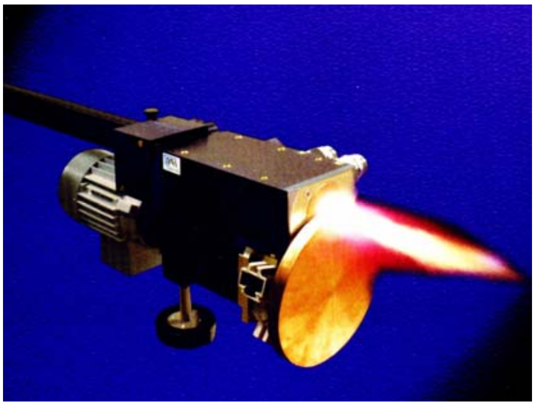


Fig.5: Photo of hybrid plasma generator

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