Physics and Chemistry of Plasma Pollution Control Technology

Jen-Shih Chang

McMaster Institute of Applied Radiation Sciences and Department of Engineering Physics, McMaster University, Hamilton, Ontario, Canada L8S 4M

The air pollution have been suggested to have a large impact not only on human health, but also on the economy, where approximately 0.06-0.09% of the population experiences premature death caused by air pollution and 2.5 to 3 times these numbers are admitted to hospital. The average cost of mortality was $4M US per person and adult chronic bronchitis cost an average $279,000 per person for treatment. Non-thermal plasma pollution control technology may assist to reduce these health and economic impacts in the near future. In this work, chemistry and physics of plasma pollution control will be discussed and limitation of this type of plasma was outlined

1. Introduction

Plasma pollution control included gaseous pollution control by non-thermal plasmas [1], thermal plasma treatment of solid and liquid wastes [2] ,and thermal and non-thermal plasma drinking and waste water treatments [3]. The majority plasma was operated under atmospheric gas pressure. Normally, the gas temperature above combustion temperature (2300K) is called thermal plasmas and the temperature below is called non-thermal plasmas. In this work, chemistry and physics of plasma pollution control will be discussed and limitation of this type of plasma was outlined.

2. Chemistry

In classical plasma chemistry, all the chemical reaction was assumed to be initiated by radical reactions and these radicals are generated by the direct impact electron molecule dissociation reactions. However, the recent computer modelling and LIF direct measurement show that radicals in a non-thermal plasma have much longer life then classical recombination based life time since these radicals can be generated through ion-molecule reactions, dissociate recombination of ions and electrons, attachment and detachment reactions, The gas temperature dependence of reaction rate is more complex depending on the vibrational excitation especially when involved electrons and this effects the role of radicals different compared with room temperatures. On the other hand, the recent kinetic modelling of thermal plasma shows significant different degree of ionization then classical Saha type ionization model and even existence of negative ions in a thermal plasma. Ion induced aerosol formation is also important process in a gaseous pollution control since aerosol surface reaction rate is a few order of magnitude faster then the electronic, ionic and radical reactions, where relative order of these reaction are summarized in Tables 1 and 2 [1] .The mechanism of non-thermal plasma gaseous pollution control hence more complex and summarized in Fig.1 [1].

3. Physics

In a non-thermal plasma gaseous pollution control, electron beam, barrier discharge, super-imposed dc/ac streamer corona discharge, flow stabilized corona discharge, and pulsed corona and pulse power techniques are used for the plasma sources. However, in order to design more efficient plasma reactor and power supply, a physics of these non-thermal plasmas must be understood. For example, the secondary gas flow due to the electrohydrodynamic origin must be actively used to reduce pressure drop of the reactor where the pumping power is highest energy used components in an industrial process. Simple model to estimate plasma parameters from discharge current, applied voltage and power will also be presented.

3.1 Stability of plasma

DC streamer corona discharge is unstable and easy to transition to spark discharges, hence the following approaches are used to stabilize discharge as summarized in Table 3 [4, 2]:

a) No sharp edge discharge electrodes;
b) Flow stabilized corona;
c) Superimposed AC/DC discharge;
d) Wall stabilized (micro-gap) discharge;
e) External magnetic field;
f) Barrier discharge;
g) Pulsed corona discharges; and
h) Plasma-catalyst based on above reactors (Fig.2).

3.2 Determination of plasma parameters

The order of magnitude of plasma parameters such as electric field E, electron temperature T_e, plasma density N_e, can be estimated by discharge current-voltage characteristics or waveforms. Discharge current consists of conduction current I_c and displacement current I_d component; $I_t = I_c + I_d$. For corona and spark discharges, the conduction current can be approximated by [4]

$$I_c = e\, N_e\, u_e\, \underline{E}\, A$$

where e is the elementary electronic charge, u_e is the mobility of electrons, and A is the electrode surface area. Hence, plasma density can be expressed by

$$N_e = I_c/e\, u_e\, \underline{E}\, A = I_c/e\, u_{eo}\, A\, E^{1+b}$$

where $u_e = u_{eo} E^b$, and w is the power law constant determined from swarm experiment [5] and u_{eo} is the electron mobility at small electric field (constant).

Electric field distribution can be determined from the Poisson's equation as follows:

$$\Lambda \,.\, \underline{E} = -e\, N_e/\gamma$$

where γ is the dielectric constant. The first order electric field assumed no space charge effect (Laplace field) normally determined from the gap distances between two electrodes d as follows:

$$E_r = V_t/d$$

where E_r is the so-called reduced electric field and V_e is the applied voltage. If Poisson field can be approximated by $E = E_r^W$, the plasma density can be determined by:

$$N_e = I_c/e\mu_{eo}\, A(V_t/d)^{w(1+b)} = c_2 I^{\alpha} = c_1\, I_c/V_t^a$$

$$a = w(1+b), \quad \alpha = w/(b+2w)$$

and electron temperature can be determined by swarm parameters [5] as follows:

$$k\, T_e/e = c_o\, E^f = c_o(V_e/d)^{f\,W} = u_e\ /De$$

where c_o, c_1, c_2 are constant depending on environmental gases.

For dry air, f and b are -0.43 and 0.501, respectively, and 0 # w # 1 for $4 << (L/L_D)^2 << 0$, where L is the characteristic length and L_D is the Debye length [5].

3.3 Other associated phenomena

The other associated physical phenomena in non-thermal plasma induced by streamer coronas are as follows [1, 2]:

a) Electrohydrodynamically induced gas flow which also assists transport of radicals and ions;
b) Photon emission especially ultraviolet (UV) light; and
c) Ion induced aerosol particle formations.

4. Engineering and Economics

For engineering of non-thermal plasmas, three components: a) power supply developments, b) reactor development, and c) overall process developments, are equally required. In order to develop scaling of systems, the specific energy density

SED = Input Electric Power/Gas Flow Rate [kWh/m^3]

and the energy efficiency of pollutant removal

E_y = g[pollutant removal]/kWh

were used, where E_y-[SED] characteristics can be used effectively to estimate economic evaluation [6] with scale-up based on the pilot scale test. Hence, experimental results are not only expressed in terms of applied voltage, current, or power, both SED and E_y are shown to be present. Typical results are shown in Fig.3 [6].

5. Concluding Remarks

The air pollution have been suggested to have a large impact not only on human health, but also on the economy, where approximately 0.06-0.09% of the population experiences premature death caused by air pollution and 2.5 to 3 times these numbers are admitted to hospital. The average cost of mortality was $4M US per person and adult chronic bronchitis cost an average $279,000 per person for treatment. Non-thermal plasma pollution control technology may assist to reduce these health and economic impacts in the near future. The fundamental study of physics and chemistry of this plasma technology will be give us an engineering baseline data for a economically feasible pollution control technology [6]. Based on research of past 30 years, type of non-thermal plasma technology for feasible for each gaseous pollutant treatments are summarized in Table 4 and Fig.4..

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Table 1 Chemical reaction and rates [1].

Tab.3-1 Chemical reactions and reaction rates

Reaction	two body reaction rate [cm^3 / s]	three body reaction rate [cm^6 / s]
molecule – molecule	10^{-14} - 10^{-31}	10^{-30} - 10^{-40}
atom / radical - molecule	10^{-11} - 10^{-24}	10^{-30} - 10^{-36}
ion – atom / molecule	10^{-9} - 10^{-13}	10^{-28} - 10^{-32}
electron - molecule / molecule	10^{-7} - 10^{-11}	10^{-27} - 10^{-35}
positive - negative ion	10^{-6} - 10^{-8}	10^{-25} - 10^{-26}
electron - ion	10^{-6} - 10^{-7}	10^{-26} - 10^{-28}
molecule / radical-aerosol	(10^{-5} - 10^{-10}) Rp(nm) Rp: diameter of aerosol	
comparison of dominant reaction [reaction rate] x [molecule density] x [reactant density] (x [third body molecule density])		

Table 2 Reaction kinetic rate equations and relative importance between ionic and radical reaction.

$$\frac{dN}{dt} = k_1[A][B] + k_2[C^+][B] - \cdots$$

where

$$A + B \xrightarrow{k_1} N + M$$

and

$$C^+ + B \xrightarrow{k_2} N + L$$

However,

$$[A] \gg [C^+];\ k_1 \ll k_2$$

Thus,

$$k_1[A] \approx k_2[C^+]$$

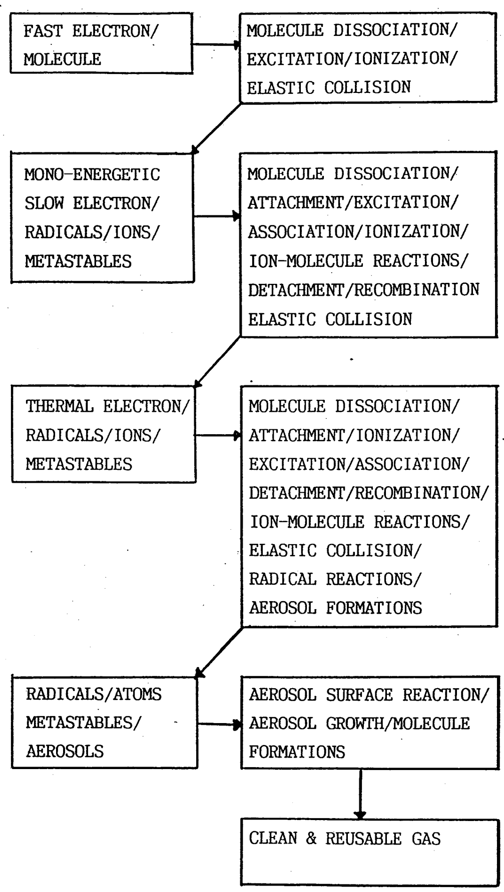


Fig.1 Mechnism of plasma pollution control [1].

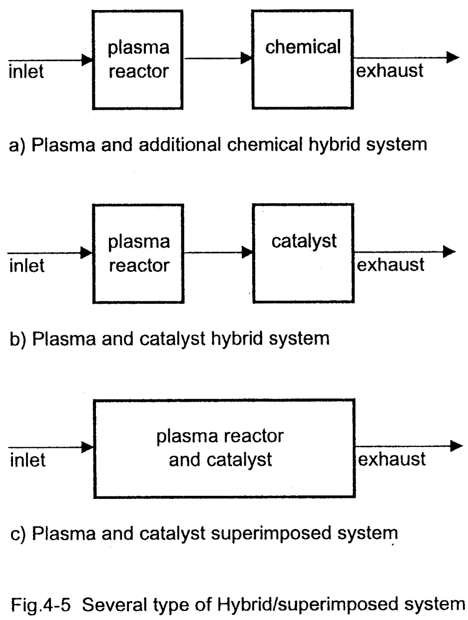


Fig.2 Plasma Catalysis

Table.3 Characteristics of various plasma systems

Tab.4-1 Characteristics of non-thermal plasma techniques (E-beam, Barrie, Pulse etc.)

	Voltage [V]	Current [A]	Frequency [Hz]	Power efficiency [%]	Pressure Drop	Flow Rate [Nm^3/h]
Electron Beam	100K-200M	1m-10(dc)	dc-100	80-95	small	10^3-10^5
Barrier discharge	5K - 20K	1m - 10	10-100k	30-80	large	10^{-2}-1
Pulsed Corona	30K - 200K	10m - 1	10-1K	20-70	middle	1-10^2
Flow stabilized Corona	10K - 100K	10μ-100m	dc	90-95	middle	1-10^2
Arc discharge	0.1K - 0.5K	10 - 100	dc	70-90	middle	10^{-1}-10
High Frequency discharge	0.1K - 0.5K	1m - 1	1k-100k	50-70	small	10^{-2}-10
Micro wave discharge	0.1K - 0.5K	1m - 1	>1G	30-60	small	10^{-2}-1

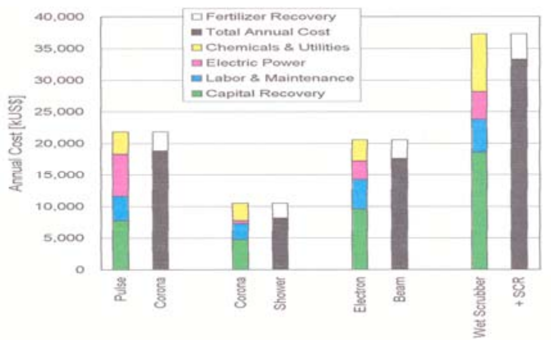
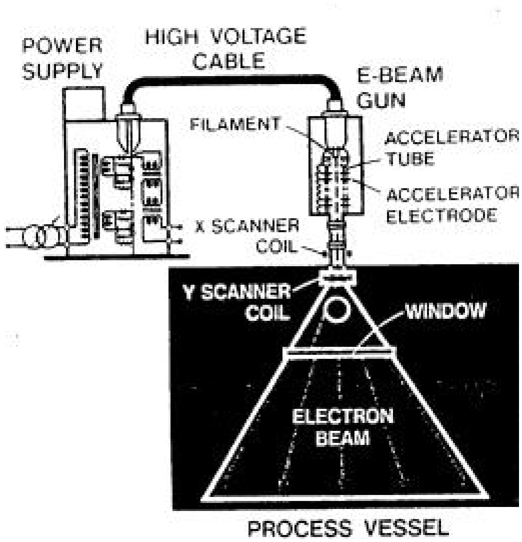


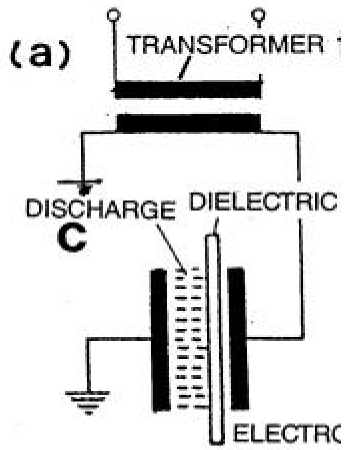
Fig.3.Economic evaluation of plasma pollution control systems

Table 4. Plasma parameters for various non-thermal plasmas and the most feasible applications [2].

Table 1 Plasma parameters for gaseous pollution control plasma devices (*Waste gas destructions)

	Plasma Density	Electron Temperature	Gas Temperature	Electric Field	Treatment Flue Gases
Electron Beam	Very High	Extremely High	Low	Very Low	Acid Gases, VOCs
Barrier Discharge (silent/surface)	High	Medium	Low	Medium	Oxidation of VOCs or Acid Gases
Barrier Discharge (ferro-electric)	Low	High	Low	Very High	PFCs, Oxidation of VOCs
Pulsed Corona	High	Medium	Low	High	VOCs
Pulsed Power	Very High	High	Medium	High	Acid Gases
Capillary	High	Low	Medium	Low	VOCs
Flow Stabilized Corona	Locally High	Locally High	Low	High	Acid Gases, VOCs, Toxic Gases
Arc/Plasma Torch	Extremely High	Locally High	Extremely High	Low	ODS/VOCs* Toxic Gases
RF Discharge	High	Medium	High	Low	ODS/VOCs*
Microwave Discharge	High	Medium	Medium	Medium	ODS/VOCs*





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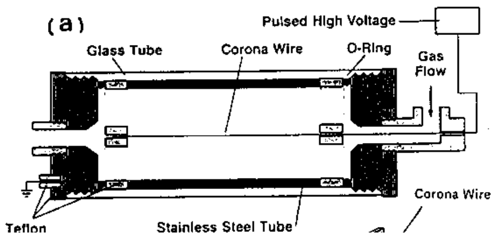

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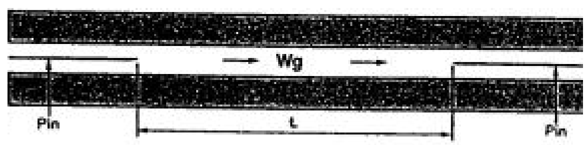

(d)

Fig.4 Typical non-thermal plasma reactors [1].(a) electron beam;(2) barrier discharge; (3) dc, pulsed or AC/DC corona; (4)wall stabilized corona.