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PLASMA-ARC TECHNOLOGY FOR THE THERMAL TREATMENT OF CHEMICAL WASTES*

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ABSTRACT

Plasma-arc technology is developed to dispose chemical wastes from a chemical plant by the Institute of Mechanics, Chinese Academy of Sciences. A demo system with this technology is constructed to destroy two sorts of chemical wastes from production process in a chemical plant of Chenguang Research Institute of Chemical Industry, Zigong, Sichuan, China. The system includes shredding, mixing and feeding sub-systems, plasma-arc reactor of 150 kW, off-gas burning and scrubbing sub-system. To form the vitrified slag, some additives, such as CaO, SiO_2 and Fe, etc., are added into the reactor. The average temperature in the graphite crucible space is in the range of 1400-1500°C, so the hazardous organic wastes with chlorine are rapidly pyrolyzed and the additives are heated up to molten state to capture the hazardous elements, then the slag is quickly quenched to form amorphous glass structure. A DC experimental facility of 30 kW with plasma-arc technology is also set up to study the pyrolysis process in the laboratory, and the experimental results show the cooling speed is the most important factor for good vitrified structure of the slag. According to previous tests, the destruction and removal efficiency (DRE) for these chemical wastes is more than 99.999%, and the PCBs concentration in the solid residues is in the range of 1.28 to 12.9 mg/kg, which is far below the National Emission Limit for hazardous wastes. A simplified electro-magneto model for numerical simulation is made to estimate the temperature and velocity fields. This model can make very satisfied maximum temperature and velocity distributions in arc region, as well as the results by magneto hydrodynamic approach.

INTRODUCTION

Public health and environment pollution have become a strong concern in China, especially after the 2003 Severe Acute Respiratory Syndrome (SARS) epidemic (1, 2). It is tremendously important to dispose of hazardous waste with high efficiency and no secondary pollution. Plasma Pyrolysis with Vitrification (PP/V) processing has many advantages for the efficient destruction of hazardous wastes; great destruction and removal efficiency for hazardous waste treatment, highly stabilized solid waste – glass-like residue, smaller reactor and auxiliary equipment, lower capital cost, fast startup and shutdown, and competitive processing cost for mixed hazardous wastes (3, 4). Because of these potential advantages, PP/V process has been developed for the destruction and removal of various hazardous waste, such as polychlorinated biphenyls (PCBs) (3), medical waste (5), metallurgical wastes, incineration fly ash (6, 7), low-level radioactive waste, etc. The results show that the PP/V technology is a state-of-the-art technology for hazardous waste destruction.

The Institute of Mechanics, Chinese Academy of Sciences (CAS), developed a 3-phase AC plasma-arc furnace for metallurgy in the 1980s, and then used the equipment to dispose of hazardous wastes in the

1990s (1, 2). Many trials have been carried out for the treatment of organic wastes, including hospital wastes, dead animal bodies, waste polymers (plastics and rubber), waste oil, pulp mill slurry, waste scoria and hazardous waste with high arsenic and sulfur concentrations. The furnace-feed waste stream can be solids, liquids or gases, even slurry, and all type of wastes can be treated. The volumetric reduction after treatment is up to 99% for organic wastes (1, 2).

A 150 kW DC pilot system with the modified plasma-arc reactor has been constructed in a chemical plant of Chenguang Research Institute of Chemical Industry, which is located in Zigong City in Sichuan Province of western China, to destroy two sorts of chemical wastes from production process in the plant. Furthermore, a 30 kW DC plasma-arc reactor has been also built up in the laboratory to study the mechanism of the formation of vitrified slag and optimizing the operation parameters for waste destruction process.

Three different mixtures of chemical waste and additives have been destroyed by the 150 kW reactor and the 30 kW reactor. The thermodynamic equilibrium product distribution of initial reactants is calculated by CHEMKIN, and the numerical simulation is made to estimate the temperature distribution and the products of the pyrolysis process. A simplified electro-magnetic simulation is also made to study the temperature and flow fields in all regions of Plasma-Arc Reactor, including the arc region and the plasma reaction region.

MATERIALS AND METHODS

Experimental Facility

Figures 1 and 2 show the reactor of the 150 kW DC pilot system in Chenguang Research Institute and a 30 kW reactor in laboratory, respectively. The 150 kW DC plasma reactor is based on a 150 kW 3-phase AC plasma reactor developed in our laboratory in the 1990s, and a rectifier was employed to get stable arc character. Figure 3 shows the schematic description of the pilot pyrolysis system. The 150 kW DC system includes shredding, mixing and feeding sub-systems, plasma-arc reactor system, off-gas burning and acid-gas recover sub-system, scrubbing sub-system, etc. The plasma-arc reactor system is composed of seven sub-systems: power supply, argon gas supply system, plasma generator and reactor, residue discharging system, cooling sub-system, special transformer and control system. The 30 kW system is simpler than the 150 kW one, but the plasma-arc system is completed.

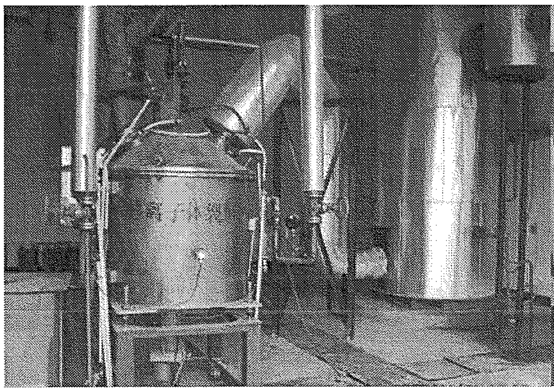

Fig. 1 Picture of plasma reactor of pilot system

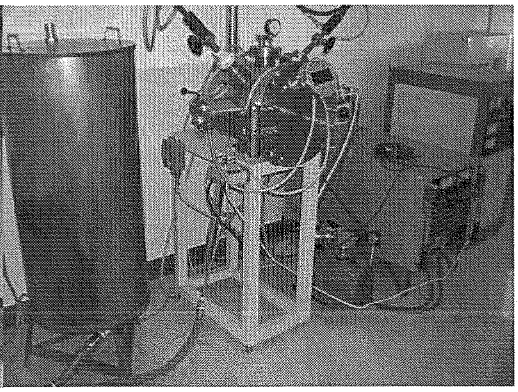

Fig. 2 Picture of the 30 kW plasma reactor

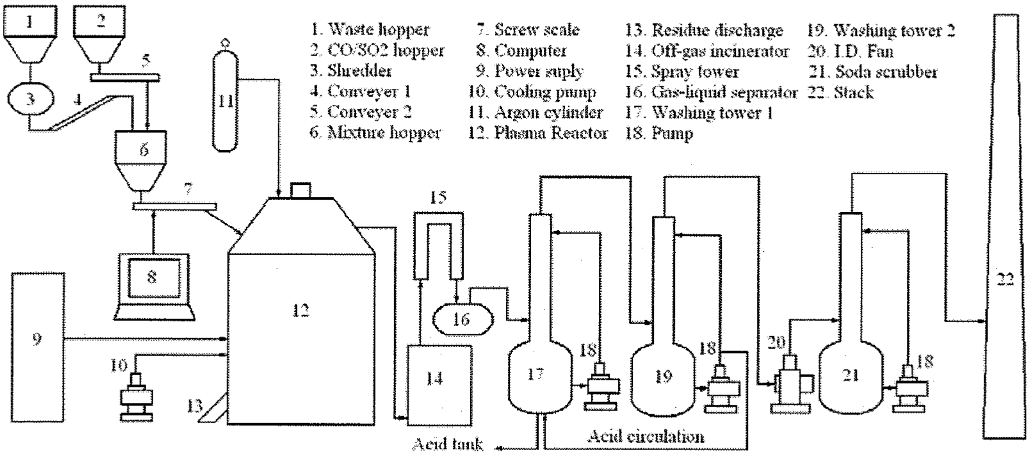

Fig. 3 A schematic description of the pilot plasma pyrolysis system

Experimental Materials

The two sorts of solid chemical wastes from chemical production lines of Second Chemical Plant of Chenguang Research Institute are marked with CW-1 and CW-2, of which compositions are shown in Table I. The elemental analysis of unknown organics (including PCBs) of CW-2 shows that it contains of carbon 62.84 wt%, hydrogen 4.28 wt%, chloride 32.78 wt% and sulphur less than 0.1 wt%.

Table I. The Major Chemical Composition of Wastes

Chemical wastes	Composition	Wt.%
CW-1	Biphenyl	80~85
	PCBs	10~15
CW-2	Silicon powder	~60
	Copper powder	~2
	Carbon compounds	25~30
	Unknown organics (including PCBs)	~10

Table II. The Mixtures of Chemical Wastes and Additives

Mixture / Composition	Mixture 1 (g)	Mixture 2 (g)	Mixture 3 (g)
CW-1	100	—	20
CW-2	—	150	20
SiO_2	—	120	15
C	100	—	—
CaO	300	150	5

To form the vitrified slag, some additives, such as CaO, SiO_2 and Fe, etc., are added into the reactor. The waste with different proportion of additives has been destroyed in this study. Table II shows three different mixtures of wastes and additives. Mixture 1 and mixture 2 are destroyed by the 3-phase AC plasma reactor in our laboratory. The experiment lasts 260 seconds with 60 kW power for mixture 1 and 330 seconds for mixture 2. Mixture 3 is investigated with the 30 kW DC plasma reactor. The average temperature in the reaction space is controlled at 1400-1500°C. In the plasma process, hazardous organic wastes are rapidly pyrolyzed and additives are heated up to molten status to capture the hazardous elements, then the molten slag is quickly quenching to form amorphous glass structure.

EXPERIMENTAL RESULTS AND DISCUSSION

The off-gases of mixture 1 and mixture 2 have been detected by National Research Center for Environmental Analysis and Measurements in China, and it is found that PCDDs, PCDFs and PCBs are not detected. The solid residue content of mixture 1 and mixture 2 are also detected, of which are shown in Table III. Destruction and removal efficiency (DRE) of chemical waste is more than 99.999%. The solid residues contain PCBs in the range of 1.28 mg/kg to 12.9 mg/kg (Table 3), which is far below the National emission limit value for hazardous wastes.

Table III. The solid residue content of mixture 1 and mixture 2

Content	Residue of mixture 1 (mg/kg)	Residue of mixture 2 (mg/kg)	Detect limit (mg/kg)
Chlorobiphenyl	1.26	12.8	0.0002
Dichlorobiphenyl	0.0217	0.122	0.0002
Trichlorobiphenyl	N.D	0.0131	0.0002
Total PCBs	1.28	12.9	0.0002

For PP/V process, the waste mixture is heated up to molten state. The heating process is long enough to react the mixture completely, after which the molten slag is quickly quenched to form amorphous glass structure. It has been found that quenching rate is the main parameter for the formation of well vitrified slag because fast quenching rate can prevent the molten slag forming a crystal phase. The slag of mixture 2, shown in Fig. 4, is composed of many small chips, which reveals that the additives with inappropriate proportion fail to form vitrified slag. The slag of mixture 3, shown in Fig. 5, is covered by soot, which is produced through pyrolysis reaction of chemical wastes.

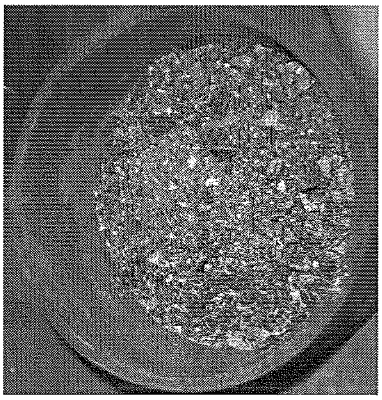

Fig. 4 slag of mixture 2

Fig. 5 slag of mixture 3

The production distribution of thermodynamic equilibrium can be calculated on the assumption that the pyrolysis reaction in the reactor rapidly finishes. CW-1 has been calculated by using CHEMKIN, which qualitatively corresponds with its experimental results. The calculation results are shown in Fig. 6, which reveals that the major products are carbon, hydrochloride, methane and hydrogen. After plasma pyrolysis, the hazardous organic waste is rapidly pyrolyzed into some simple molecules, which are harmless and combustible. The hydrochloride can be neutralized by NaOH solution; refer to the schematic description of the system. The test result shows that plasma pyrolysis technology can perfectly meet the most stringent emission standard for hazardous waste.

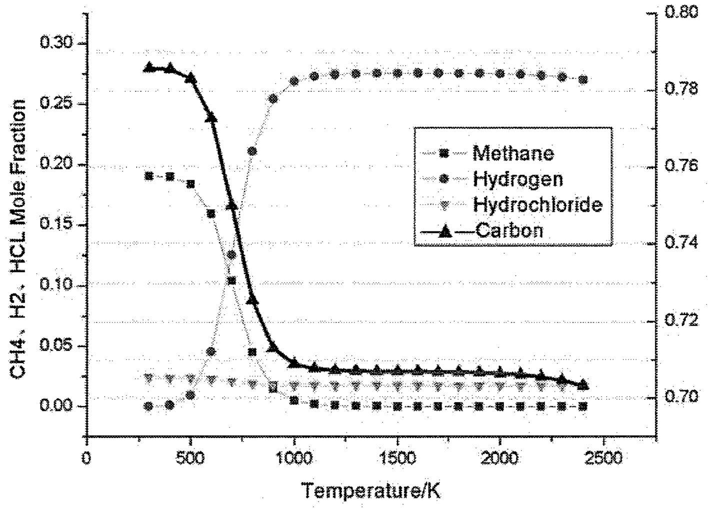

Fig. 6 The calculation result of CW-1

NUMERICAL SIMULATION

Numerical simulation of the 30 kW DC plasma-arc reactor is made to estimate the temperature and velocity fields. The simulation region including the arc region and the plasma reaction region (Fig. 7) is for a half reaction zone of 30 kW reactor since the reactor is symmetric.

The governing equations for the plasma-arc reactor can be written as follows (8):

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial z}(\rho v_z)=0 \qquad \text{(Eq. 1)}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r^2)+\frac{\partial}{\partial z}(\rho v_r v_z)=-\frac{\partial P}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}(2r\mu\frac{\partial v_r}{\partial r})+\frac{\partial}{\partial z}[\mu(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z})]-2\mu\frac{v_r}{r^2}+S_r \qquad \text{(Eq. 2)}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_z)+\frac{\partial}{\partial z}(\rho v_z^2)=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial z}(2\mu\frac{\partial v_z}{\partial z})+\frac{1}{r}\frac{\partial}{\partial r}[r\mu(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z})]+S_z \qquad \text{(Eq. 3)}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho c_p v_r T)+\frac{\partial}{\partial z}(\rho c_p v_z T)=\frac{1}{r}\frac{\partial}{\partial r}(rk\frac{\partial T}{\partial r})+\frac{\partial}{\partial z}(k\frac{\partial T}{\partial z})+S_R \qquad \text{(Eq. 4)}$$

Eq. 2 and 3 include a volumetric source of momentum in both the radial and axial direction, respectively S_r and S_z, which represents the Lorentz Force effect to velocity field, while Eq. 4 includes a heat source S_R, which consists of the Joule-heating term, the radiation term, and an additional term that represents the transportation of electron enthalpy due to the drift of the electrons.

In previous studies, the magneto hydrodynamic approach is normally introduced to simulate the small arc region, but it is difficult to be applied in reaction region for waste treatment. In the present work, a simplified electro-magneto model (Fig. 7) is developed to simulate both arc region and reaction region, which can reduce the number of governing equations and reduce CPU time greatly, especially for employing waste reaction simulation by chemical kinetics. In this model, the temperature profile along the arc boundary is as a known parameter according to the measured data (10). Based on the constant electrical conductivity assumption of the arc channel theory, by transforming the Maxwell equations, the electric current density profile of the arc region can be obtained, and hydrodynamic approach combining of additional sources is applied to simulate the temperature and velocity field. This simplified model is important to the reaction for waste treatment process.

The electric current density distribution along the cathode $j_z=j_{max}exp(-br)$ is assumed in the model. The electric potential along the anode is set to zero. The ambient gas is argon, and the plasma properties are taken from (10). The $k-\varepsilon$ two equations model is introduced to simulate turbulence. The radiation transfer is the main phenomenon in the plasma-arc reactor, the discrete transfer radiation model (DTRM) is used to calculate this transfer, and the gray radiation is assumed. Some of the boundary conditions for the enthalpy are defined in terms of temperature; these are then converted into the enthalpy of the appropriate gas. The cathode temperature is assumed as about 3000K, approximating the free-burning arc cathode temperatures measured by Haidar and Farmer (11). The electric potential along the cathode is defined by specifying electric current density. As expected, the heat loss due to the water cooling side-wall is a sensitive parameter. The boundary conditions of the bottom-wall and the side-wall are illustrated in Fig. 8. Simulation result shows that energy of 65% is transferred to the side-wall, and the adiabatic wall is important for reactor.

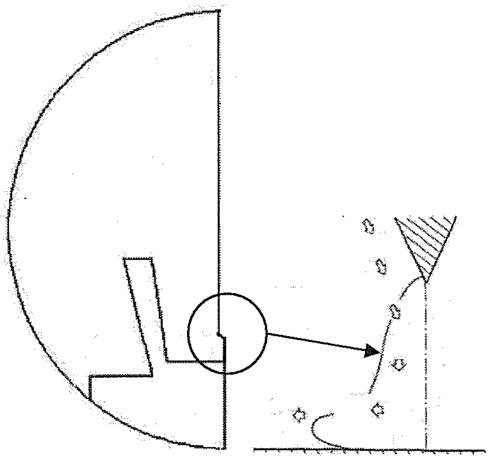

Fig. 7 Simulation region

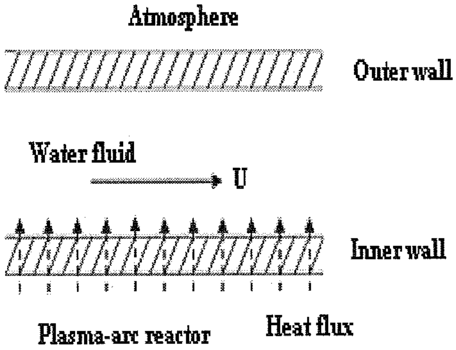

Fig. 8 Water-cooling model

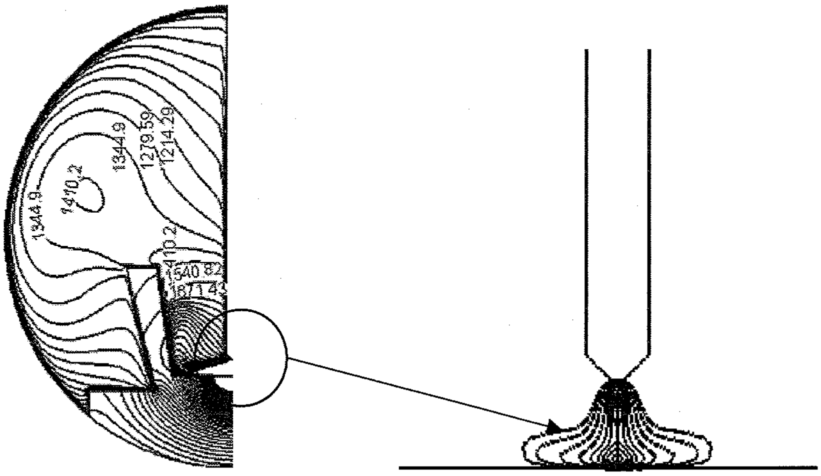

Fig. 9 Contours of temperature in the whole reactor (left) and the arc region (right. zoomed)

Several preliminary numerical studies were carried out in order to choose the optimum parameters for tests. Figure 9 shows the temperature simulation results where the temperature of the arc region is very high, while the temperature in reaction region is about 1400K and is almost uniform. The temperature along the radial aspect decrease rapidly. The results show that the velocity is about 2m/s in the reaction region, and the maximum velocity in arc region can reach 300m/s (refer to Fig. 10).

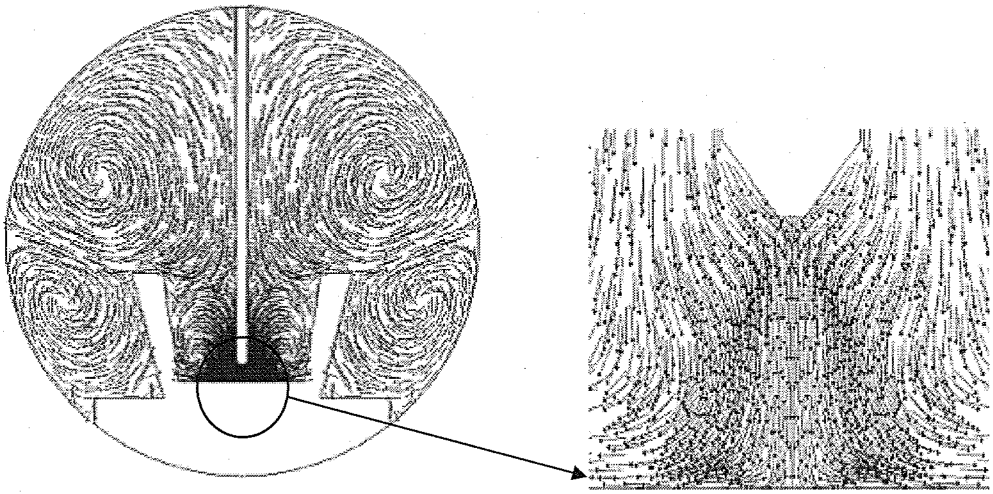

Fig. 10 Velocity vector in the whole reactor (left) and the arc region (right. zoomed)

Figure 11 shows a comparison between the results of the magneto hydrodynamic approach and the present simplified model. The present work is very good in agreement with the maximum temperature and maximum velocity distributions in arc region (8). The results indicate that the simplified model can be a useful tool for further study.

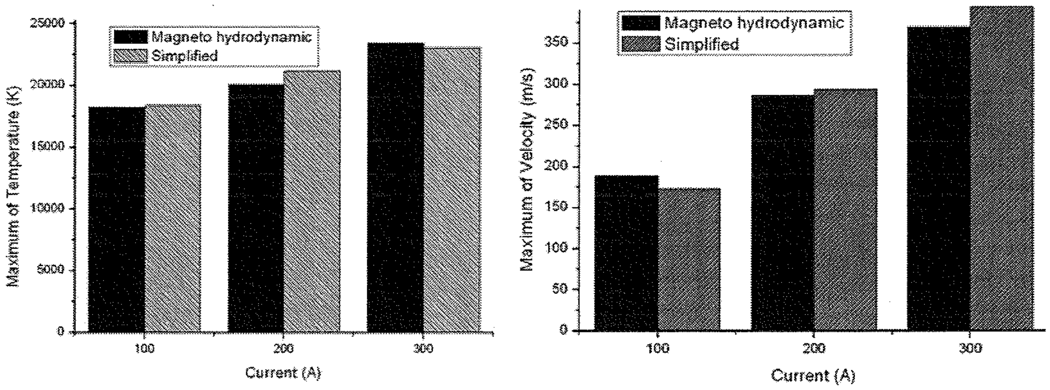

Fig. 11 Comparisons of maximum temperature (left) and velocity (right) in arc region

The numerical results presented in this paper are preliminary results, the next step for the process simulation is taking the chemical kinetics into model.

CONCLUSIONS

1. A pilot system with PP/V technology is constructed to destroy two sorts of chemical wastes from production process in Second Chemical Plant of Chenguang Research Institute of Chemical Industry, Zigong City, Sichuan Province of China. The destruction of hazardous chemical waste has been studied by using a 150 kW 3-phase AC plasma-arc reactor. A 30 kW DC experimental facility with plasma-arc technology was also set up in our laboratory to study the pyrolysis process.

2. During the plasma pyrolysis process, the hazardous organic waste is rapidly pyrolyzed into some simple molecules and the major products are hydrogen, hydrochloride, methane, carbon, which qualitatively corresponds with calculation results by using CHEMKIN. It is found that PCDDs, PCDFs and PCBs are not detected in the off-gas. Destruction and removal efficiency (DRE) for these chemical wastes is more than 99.999%, and the PCBs concentration in the solid residues is in the range of 1.28 to 12.9 mg/kg, which is far below the National Emission Limit for hazardous wastes.

3. For the plasma vitrification process, additives are added into the reactor. It is found that the quenching rate is the main parameter for the formation of shiny and dense vitrified slag with glassy structure. However, some of vitrified slags gained in the present work are incompact and mat, which reveals that the additives with inappropriate proportion fail vitrification process.

4. A simplified electro-magneto simulation was made to estimate the temperature distribution and the products of the pyrolysis process, the result shows that this simplified mode can make very satisfactory arc temperature and velocity fields in arc region as well as the results from magneto hydrodynamic approach.

Footnotes

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