Research on optimal control of low power thermal plasma field for waste gas treatment

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Abstract. The innocuous treatment of solid waste, waste gas and other pollutants has become a major environmental protection problem that needs to be solved urgently in China's green development. Aiming at the problems of low efficiency and secondary pollution of traditional waste gas treatment methods, the use of high temperature generated by thermal plasma and active particles to quickly decompose and destroy pollutants and eventually form stable harmless substances has proven to be an effective way. This article studies a method that can stably generate thermal plasma in a low-voltage. By adding an auxiliary high-voltage electrode to the front end of a hot plasma sliding arc, it helps the thermal plasma device to more easily penetrate the air for arcing. By using a flow meter and a fan to change the flow field of channel. The arcing conditions of the device under different flow fields was investigated. And by studying the influence of input power and air flow velocity on the arc length and period of the arc, the contact situation between the thermal plasma arc and the gas is obtained. The experimental results show that a stable and appropriate flow field environment is the key to the efficient work of thermal plasma.

1. Introduction

With the rapid development of China's industry, the emissions of solid waste mainly consisting of foundry waste sand, incineration of fly ash and waste gas from spraying, printing, and rubber industries have increased rapidly. In the field of detoxification of pollutants, widely used technologies include adsorption[1] and condensation[2] technologies mainly based on physical deposition, photocatalysis[3], combustion[4] and biodegradation[5] technologies based on chemical reactions. Thermal plasma technology is a very valuable technology introduced in the field of pollutant treatment in recent years. Thermal plasma technology can convert electrical energy into concentrated heat, and the temperature in the area of energy concentration can reach more than 3000 ℃, in this temperature range, it can completely decompose some difficult-to-decompose substances, such as dioxin. In the literature[6], Liu et al. used thermal plasma to treat methane and toluene; In the literature[7], Liu Z W heated hydrocarbons by high temperature, high enthalpy and high activity thermal plasma In order to make it quickly crack and convert to acetylene; In the literature[8], Du et al. analyzed the principle and characteristics of thermal plasma treatment of various different hazardous wastes. However, at present, in terms of the harmless treatment of pollutants by thermal plasma technology[9,10], the technical route adopted is to inject the torch generated by thermal plasma into the waste gas channel or the combustion chamber to decompose the pollutants. Due to the temperature
gradient of the torch energy during the transfer process, it takes a certain amount of time to achieve thermal equilibrium. Therefore, the thermal plasma technology using the injection method requires the waste gas to stay in the space where the thermal plasma acts for at least 2s, resulting in a large equipment volume and a complicated structure.

In order to solve the problem of thermal plasma in the harmless application of waste gas, a thermal plasma generator using low-voltage high-current power supply as the main driver of thermal plasma and high-voltage low-current power supply as auxiliary arc starting was developed in this paper, through flow field analysis and experiments, to provide a theoretical basis for the improvement and design of thermal plasma equipment.

2. Thermal plasma experimental device

The experiment was carried out in an open environment at a temperature of 25℃. The thermal plasma platform used in the experiment is shown in Figure 1. The entire system consists of power supply, electrode, gas supply system, and gas path. The output voltage of the high-voltage power supply is 3KV to 18KV, the output current is 30mA, and the output power is 500W. Air compressor and fan provide waste gas. Use the digital clamp multimeter UT200 to measure the actual current of the thermal plasma power supply. By using the gas channel or combustion chamber as a part of the thermal plasma generator. The waste gas passes directly through the thermal plasma field, and is rapidly ionized and decomposed in the arc region of the plasma generator. This not only can greatly reduce the volume of the treatment equipment, but also simplifies the structure of that. The working mode of thermal plasma is sliding arc discharge[11,12], which generates a plasma field on the sliding surface, which increases the contact area between the gas and the plasma flame, and improves the efficiency of the waste gas treatment. In addition, due to the high current of the thermal plasma generating device, the sliding arc discharge can extend the "point" area to the "surface" area generated by the electric corrosion, greatly extending the service life of the plasma generator electrode. The basic principle of the sliding arc is to form an arc at the narrowest point of the electrode. The arc slides along the direction of the airflow. As the distance between the electrodes gradually increases, the voltage required across the corresponding arc also increases with the length of the arc. When the required voltage exceeds the maximum voltage that the power supply can provide, the arc will be disconnected and regenerated at the smallest point, and continue this cycle.

![Figure 1. Schematic view of the experimental device.](image-url)
The plasma generating device is shown in Figure 2. The two electrodes are symmetrically placed. Point O is a fixed point. The electrode can rotate around this point. R1 is the radius of the electrode arc and R2 is the distance between the two fixed points of the electrode. θ is the opening angle between the electrodes. d is the pole between the electrodes. It is guaranteed that the minimum distance between the electrodes remains unchanged when the electrode angle is changed.

Because the main electrode uses a low-voltage and high-current power supply, it cannot directly penetrate the air to generate an arc. Therefore, by adding an auxiliary high-voltage electrode at the front end of the main electrode, the electrode is connected to the high-voltage power supply to directly penetrate the air, thereby generating enough charged particles, which reduces the electrical conductivity of the air between the main electrodes, reducing the electrical conductivity of the air between the main electrodes, and directing these charged particles into the main electrodes by the action of the airflow. The auxiliary high voltage electrode still adopts the design idea of sliding arc, and it is placed in a cross with the electrode, as shown in Figure 3.

![Figure 2. The device of gliding arc discharge.](image)

![Figure 3. Location of auxiliary high voltage electrode and main electrode.](image)

3. Gas channel simulation analysis
In order to solve the problem of thermal plasma in the harmless application of waste gas, this paper uses the waste gas channel or combustion chamber as a part of the thermal plasma generator.

This experimental device generates a thermal plasma arc with a low-voltage power supply. The charged particles generated by the auxiliary high-voltage electrode at the front are blown between the main electrodes by the airflow. Change the dielectric constant of the gas between the working electrodes, reduce the insulation of the air, and make it easier for the main electrodes to arc in low voltage conditions. However, the flow direction of the charged particles is determined by the flow field, so the flow field and flow rate of the carrier gas will inevitably have a significant effect on the plasma characteristics. This requires flow field analysis and experimental verification of the flow channel of the entire thermal plasma equipment. It is necessary to conduct flow field analysis and experimental verification of the gas channel of the entire thermal plasma equipment.

3.1. Streamline model simplification and assumptions
The fluid flow simulation software CFX 15.0 developed by British AEA Technology company was used to simulate the flow channel. The following assumptions were made in the simulation.

1. The air temperature is set to 25°C.
2. Plasma is generated in the air, so the plasma is set to a laminar flow state.
3. Plasma is an incompressible fluid, which makes steady flow. The thermodynamic properties and fluid properties of a given point are determined by temperature and pressure.
4. Set the plasma to Newtonian fluid.
(5) Set the fluid object to steady state.

3.2. Hydrodynamic governing equation

Fluid flow is subject to the laws of physical conservation. The basic conservation laws include: conservation of mass, conservation of momentum, and conservation of energy.

Because we are studying the steady-state mechanics problem in the two-dimensional plane, the mass conservation equation for the control of the flow field is shown as Eq. (1)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Any fluid system must satisfy the law of conservation of momentum, which indicates that the rate of change of the momentum of the fluid in the microelement body against time is equal to the sum of various forces acting on the microelement body. Referring to this law, the momentum conservation equation for flow field control is shown as Eq. (2)

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i$$

Where $\rho$ is the fluid density; $p$ is the static pressure; $\tau_{ij}$ is the stress tension; $g_i$ and $F_i$ are the gravitational volume force and the external volume force in the $i$ direction; the unknown quantities $u_i$ and $u_j$ of the required solution represent the velocity vector $u$ at $i$ or $j$ direction components.

The energy conservation equation in a fluid problem is shown as Eq. (3)

$$\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho u T) = \text{div} \left( \frac{k}{c_p} \text{grad} T \right) + S_T$$

Where $T$ is the temperature; $k$ is the heat transfer coefficient of the fluid; $c_p$ is the specific heat capacity; $S_T$ is the viscous dissipation term; $\rho$ is the density; $t$ is the time; $\text{div}$ is the divergence; $\text{grad}$ is the gradient; $u$ is the velocity vector.

The distribution of velocity field under special boundary conditions can be obtained by simultaneous Eq (1), (2) and (3).

3.3. Experimental improvement based on simulation analysis

For this experimental device, the entire space of the gas channel from the inlet to the outlet is used as the calculation domain. The gas channel is shown in Figure 4: the size of the fan inlet is 60×70mm, and the outlet diameter is 100mm.

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**Figure 4.** Gas channel entity.

**Figure 5.** Gas channel simulation diagram.
Build a network by using professional pre-processing software ANSYS ICEM CFD. Taking into account the calculation speed and the quality of the grid, the number of the grid was set above $3 \times 10^4$. Because the horizontal direction of the experimental device is symmetrical structure, the flow field in the vertical plane is mainly analyzed. Set the fan output wind speed to $5 \text{ m/s}$. The flow field in the gas channel is shown in Figure 5:

![Figure 5](image)

**Figure 5.** Flow field in the gas channel.

It can be seen from the Figure 6 and Figure 7 that the airflow is obviously deposited at the bottom in the cylindrical reaction zone, and the airflow is unevenly distributed.

In order to solve the above problem, by adding a guide plate at the inlet of the fan, the length of the deflector is set to 45mm and the thickness is 4mm. Velocity cloud diagram of the flow field is measured when the angle between the guide plate and inlet plane is 30°, 45° and 60° respectively.

![Figure 6](image)

**Figure 6.** Velocity Cloud diagram.

![Figure 7](image)

**Figure 7.** Pressure cloud diagram.

![Figure 8](image)

**Figure 8.** Guide plate angle 30°.

![Figure 9](image)

**Figure 9.** Guide plate angle 45°.

![Figure 10](image)

**Figure 10.** Guide plate angle 60°.

It can be seen from Figure 8 to 10, taking the cylinder axis of the flow channel as the center line, when the angle is 45°, the airflow flows faster under the pipe, and there is a low-speed area in the center part. When the angle is 60°, there is a large difference in the speed of the airflow around the center line; when the angle is 30°, the axial airflow velocity around the center line is more stable. Therefore, the angle of the guide plate in the subsequent experiments is 30°.

After obtaining a smooth airflow, the excited charged particles will be affected by the electric field force and the free gas diffusion, which is not conducive to the accumulation of charged particles in the center of the working electrode. To solve this problem, an auxiliary air inlet pipe is installed in the center of the reaction zone of the device. At the same time, in order to balance the quality and speed of calculation. The simulation object selects only a part of the plasma reaction channels, as shown in Figure 11. This region is a plasma generating region including main electrodes and high-voltage auxiliary electrodes. The gas velocity of the auxiliary inlet pipe channel is set to be smaller than the
external one. In this simulation, the flow velocity is set to 3 m/s. Coupling simulation of two airflows was performed to obtain the airflow velocity on the axis of the reaction tube and the air pressure parameters at the cross section of the electrode.

![Figure 11. Schematic view of the experimental device.](image)

![Figure 12. Velocity Cloud diagram.](image)

![Figure 13. Pressure cloud diagram.](image)

As shown in Figure 12: There are high-voltage parts on both sides of the main electrode. The reason is that the space occupied by the main electrode near the air inlet is small, and the larger the space is taken in the direction of gas flow. As a result, the gas is compressed and the air pressure increases when the airflow passes. However, the pressure around the inner wall of the pipe is about 1.7 Pa, and the pressure at the center of the pipe is 1.25 Pa. The pressure gradually decreases from the inner wall to the center. A low pressure area is formed in the center of the electrodes, and the gas will move closer to the center under the effect of pressure. And from Figure 13: it can be concluded that the airflow velocity near the axis is about 4 m/s, lower than the airflow velocity of wall of the pipe, which is 5.5 m/s. It shows that the addition of the auxiliary air inlet pipe effectively binds the excited charged particles between the main electrodes, so as to ensure that the main electrodes can start the arc more easily.

4. Effect of air velocity on thermal plasma arcs
The thermal plasma generator of this device is based on a sliding arc. The longer the arc stretches during discharge, the greater the contact area with the gas, and the higher efficiency of the plasma arc. The state and frequency of the arc will be directly affected by the power supply and air velocity.

4.1. Effect of power supply and air flow velocity on thermal plasma arc
Both the input power of the power supply and the airflow velocity are important factors affecting the arc state of the thermal plasma, as well as two important parameters controlled by the thermal plasma generator. Set the camera to capture the instantaneous state of the arc operation every 0.2 s. Define \( t \) as a period of the plasma arc from excitation—elongation—fracture, and define \( L \) as the longest distance that the arc slides on the electrode.
The air flow velocity is selected to be 5, 7, 9, and 11 m/s, and the power input power is set to 400, 560, 640, and 720 W, respectively. Design cross experiments to intersect these parameters to study the state of thermal plasma.

Figure 14. Air flow velocity—arc cycle curve at different input power.

Combining Figure 14 and Figure 15, when the airflow velocity or input power is small, the distance the arc is driven is short, and the arc period is the same. In the case of a certain airflow, increasing the input power can effectively improve the arc period, if continued Increasing the input power does not obviously extend the arc period; Under certain power conditions, increasing the airflow velocity will increase the arc sliding distance, However, if you continue to increase the air flow rate, the sliding distance of the arc will be reduced.

The generation efficiency of thermal plasma arc is studied under the condition that the input power and airflow velocity are known to the arc state. In order to simplify the calculation and more accurately reflect the contact between the arc and the air, the contact between arc and gas is expressed by the area that arc passes between electrodes.

The Angle $\theta$ between the electrodes is set to 10°. The area swept by the arc from 0 to L in an arc period is $S_L$ in Eq. (4)

$$S_L = \int_0^L (4 + 2l\tan\frac{\theta}{2})dl$$  \hspace{1cm} (4)

the contact efficiency is shown as Eq. (5), $t$ represents the arc period and $P$ represents the input power. the greater the value, the higher the contact efficiency between plasma and gas.

$$\eta = \frac{S_L}{t \cdot P}$$  \hspace{1cm} (5)

The results are shown in Figure 16. The influence of airflow velocity on the arc efficiency is greater than the input power.

Figure 16. The contact efficiency between arc and gas under different conditions.
5. Conclusion
Thermal plasma provides a very promising solution for the treatment of pollutants such as solid waste and waste gas. Using high-voltage auxiliary electrode generates charged particles to reduce the dielectric constant of the air flowing between the hot plasma electrodes, so that the low-voltage power supply can penetrate the air to generate a thermal plasma arc. Solve the problem of high energy consumption of the system. In addition, through flow field analysis and experimental verification, an external condition can be obtained that allows the thermal plasma arc to be generated smoothly. By studying the current sliding distance and arc period, the contact efficiency between Thermal plasma arc and gas under different flow velocity and input power is obtained, which provides guidance for the application of hot plasma in waste gas treatment.

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