Three-Dimensional Effects of Torch Arrangement on the Thermo-Fluid Fields inside the Plasma Furnace

Jianwei Wang¹, Manli Guo²,³, Pingyang Wang¹* and Guanrong Hang²,³

¹School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
²Shanghai Institute of Space Propulsion, Shanghai 201112, China
³Shanghai Engineering Research Center of Space Engine, Shanghai 201112, China

E-mail: *wangpy@sjtu.edu.cn

Abstract. Numerical simulation was proposed here to investigate the three-dimensional effects of torch arrangement on the thermo-fluid fields inside the plasma furnace in a plasma medical waste treatment system. Different turbulence models were used and the simulation results were compared with previous measurement results. The effect of the torch arrangement on the flow and temperature fields was clarified by different rotary-cutting angles. It is shown that the torch arrangement affects strongly the thermo-fluid fields. An appropriate rotary-cutting angle is beneficial to safe and complete decomposition of the medical waste due to a more uniform temperature distribution inside the furnace. Besides, the life of the furnace would be greatly shortened for the case where the rotary-cutting angle is 0° because the thermal plasma jets converged in the central area of the molten pool and caused severe thermal shocks to the furnace throat.

1. Introduction

Medical waste carries a large number of highly infectious viruses and germs that may cause the spread of various infectious diseases, which poses a huge threat to the ecological environment and human health [1-3]. Thermal plasma treatment of medical waste technology, which can potentially offer greater waste volume reduction, better emission control, and the ability of generating fuels or synthetic precursors, has attracted widespread attention recently [4-6]. The technology can quickly and efficiently kill various pathogenic micro-organisms by using high-temperature thermal plasma jets. The organic matter in the medical waste can be quickly pyrolyzed and gasified into syngas, while the inorganic part is vitrified into a stable and recyclable glassy product [7-10]. Besides, the process is mainly completed in a reducing atmosphere because of a low air coefficient, which greatly reduces not only the amount of smoke emitted but also the possibility of generating harmful substances [5, 11, 12].

Several laboratory-scale plasma configurations were developed to investigate the influence of different operating parameters on thermal plasma treatment of medical waste [13]. Plasma treatment products were also explored in previous literatures [14-18]. Besides, different plasma torches (e.g., DC, AC plasma torches and so on) were used to treat medical waste [16]. However, there are few reports on the flow and temperature fields inside the plasma furnace. The thermo-fluid fields not only have a huge impact on the process of medical waste pyrolysis-gasification but also pose a serious threat to the refractory bricks inside the furnace, especially when the high-temperature plasma jet approaches the refractory bricks, which would rapidly cause severe damage to the refractory bricks. To analyze the
influence of the thermo-fluid fields on the pyrolysis-gasification of medical waste and refractory bricks, it is necessary to explore the flow and temperature characteristics inside the furnace.

In this study, the flow and temperature fields will be calculated through numerical simulation. Several turbulence models will be used, and the simulation results will be compared with previous measurement results. Additionally, three-dimensional effects of the torch arrangement on the thermo-fluid fields will be analysed and discussed. The structure of this paper is as follows: Section 2 provides a detailed description of simulation model. In Section 3, simulation results are presented and then discussed. Conclusions are drawn in Section 4.

2. Simulation analysis

The thermo-fluid fields are affected by many factors such as torch arrangement, air coefficient and temperature, system power and so on. In this study, the influence of torch arrangement is mainly explored to guide the plasma furnace design. The furnace proposed here is equipped with three plasma torches, as shown in figure 1. The three plasma torches were placed in a rotary-cutting type, as shown in figure 1 (b). To explore the influence of the rotary-cutting angle ($\alpha$) on the thermo-fluid fields, different angles ($0^\circ$, $5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$) were used in this simulation. In this study, a three-dimensional steady-state modelling approach was adopted. To simplify the simulation, the numerical simulation mainly explores flow and temperature fields without considering medical waste and the following assumptions are introduced. The plasma is optically thin and in local thermodynamic equilibrium (LTE). The plasma flow is turbulent, but the effect of compressibility is ignored.

![Figure 1. Schematic diagram of the thermal plasma furnace](image)

A three-dimensional model of the furnace was built, as shown in figure 2 (a). Velocity and temperature distribution at the nozzle exit serve as the inlet boundary conditions of the computational domain, as used in literature [19]. A tetra/mixed grid generated by ICEM CFD software is used. The boundary layer is resolved by not less than 16 finite volumes perpendicular to the corresponding walls to ensure that mesh $y+$ is smaller than 1 to meet the requirement of turbulence models. The grid independence verification has been carried out, as shown in figure 2 (b). The numbers of the grid available for numerical simulation analysis are approximately 3.2 million, 4.2 million, and 5.6 million for the computational domain. It can be concluded from figure 2 that the simulation results are not sensitive to mesh numbers. When the number of the grid reaches 4.2 million, the simulation results remain almost unchanged. Therefore, the grid with 4.2 million elements for the simulation analysis is used. Simulation analysis which uses the finite volume method was carried out by FLUENT software.
3. Results and discussion

3.1. Verification of turbulence models

Several turbulence models (e.g., standard k-ε, RNG k-ε, standard k-ω, and SST k-ω) had been tried to simulate the plasma flow, and the results were compared with measurement results [20], as shown in figure 3. It can be seen that the SST k-ω performs much better than other turbulence models. This can be explained by the fact that the inner region of plasma flow is much laminar because the Reynolds number is lower due to the higher viscosity value and lower mass density, whereas the outer region is much turbulent because the flow interacts violently with its surrounding gas [21]. However, both the standard k-ε and RNG k-ε model are only valid for fully turbulent flows. The standard k-ω model, which incorporates modifications for low-Reynolds number effects and shear flow spreading, is only valid for low-Reynolds number flows. Compared with the standard k-ω model, the SST k-ω model not only includes all the refinements but also accounts for the transport of turbulence shear stress, which makes it more accurate for a wide range of flows [22]. Therefore, the SST k-ω model was adopted throughout the following numerical simulations.
3.2. Effect of rotary-cutting angle on the flow field

Figure 4 presents the flow velocity distribution diagrams in the transverse and longitudinal sections inside the furnace for different rotary-cutting angles. a: \( \alpha = 0^\circ \). b: \( \alpha = 5^\circ \). c: \( \alpha = 10^\circ \). d: \( \alpha = 15^\circ \). e: \( \alpha = 20^\circ \). f: \( \alpha = 25^\circ \).

Figure 4. Flow velocity distribution diagrams in the transverse and longitudinal sections inside the furnace for different rotary-cutting angles. The flow velocity inside the furnace is relatively higher near the entrance of the plasma jet, and decreases rapidly as the position rises. For the case where the rotary-cutting angle is \( 0^\circ \), the velocity in the central area is obviously larger than that in the outside, while velocity distribution is reversed when the rotary-cutting angle is larger than \( 0^\circ \) as shown in the transverse sections. When the rotary-cutting angle is \( 0^\circ \), it can be found that the velocity in the central area is as high as 15 m/s, which is much larger than that in the case where the rotary-cutting angle is \( 0^\circ \). This is due to the fact that three high-speed plasma jets shoot toward the central area of the furnace and cause severe disturbances when the rotary-cutting angle is \( 0^\circ \), which results in an extremely unstable flow field. When the rotary-cutting angle is greater than \( 0^\circ \), plasma jets in the central area exhibit tangential circular flows, as shown in figure 4. Besides, the size of the tangential circular flow increases as the rotary-cutting angle increases.

In the longitudinal direction, the flow field when the rotary-cutting angle is \( 0^\circ \) is completely different from that when the angle is larger than \( 0^\circ \). For the case where the angle is \( 0^\circ \), the flow moves upward in the area above the throat of the furnace. Besides, backflow appears near the throat, as shown in figure 4 a. When the angle is greater than \( 0^\circ \), the flow forms a large-scale recirculation inside the furnace. It
can be seen that the flow near the furnace sidewall shows an upward trend. However, the flow changes direction and flows downward in the central area when it reaches the furnace top wall. Compared with the case where the rotary-cutting angle is 0 °, the recirculation in the cases where the rotary-cutting angle is larger than 0 ° can significantly improve heat and mass transfer performance between the high-temperature flow and medical material during the actual medical waste treatment process.

3.3. Effect of rotary-cutting angle on the temperature field

Figure 5. Contour map of temperature in the transverse and longitudinal section inside the furnace for different rotary-cutting angles. a: α = 0 °, b: α = 5 ° , c: α = 10 °, d: α = 15 °, e: α = 20 °, f: α = 25 °

Figure 5 is the temperature contour map in the furnace section corresponding to different rotary-cutting angles. For the case where the rotary-cutting angle is 0 °, three high-temperature plasma jets shoot toward the central area of the molten pool, causing the local temperature to rise sharply. Then, the high-temperature plasma flow in the central area expands rapidly, which results in severe thermal shocks to the bottom and throat of the furnace. In this case, the life of the refractory brick is greatly shortened. At the same time, it is difficult to form a uniform temperature field inside the furnace. For the case where the rotary-cutting angle is larger than 0 °, a rotating flame is formed in the central area, which can not only effectively avoid severe thermal shocks to furnace walls but also is conducive to a uniform temperature field.
Obviously, medical waste cannot be heated evenly during the actual medical waste treatment process for the case where the angle is 0 °, which can easily result in insufficient pyrolysis and gasification and thus produce a large number of harmful substances. As the rotary-cutting angle increases, the spiral movement of the flow drives the high-temperature plasma jets upward spirally, which avoids local high-temperature zones. It can be seen that the temperature distribution in the upper area of the furnace presents a “V” shape when the rotary-cutting angle is larger than 0 °, as shown in figure 5. This is because the high-temperature flow spirals upward in the area near the sidewall, while the syngas with a relatively low temperature spirals downward in the central area.

When the rotary-cutting angle is larger than 0 °, the syngas with little oxygen spirals downward in the central area, which provides a high temperature and low oxygen content environment for the drying and pyrolysis of medical waste in the actual treatment process. After the medical waste is dried and pyrolyzed, its residues such as coke move to the lower side of the furnace. The coke encounters and reacts with the air introduced from the air supply system near the throat of the furnace. This process, which is known as the gasification process, can easily lead to a sharp increase in local temperature due to a large amount of heat produced during the process. When the rotary-cutting angle is 0 °, the high-temperature area in the furnace is mainly concentrated in the inner part, which undoubtedly increases the risk of a local extremely high-temperature area near the throat caused by the gasification process. For the case where the rotary-cutting angle is larger than 0 °, the temperature in the inner part is relatively lower, which can effectively reduce the possibility of local high-temperature areas. Besides, the spiralling downward syngas that contains a large amount of CO₂ and water vapor encounters and reacts with the coke to produce more CO and H₂ near the throat, which not only reduces the amount of air required but also increases the content of combustible gas in syngas.

4. Conclusions
The numerical simulation was adopted to analyze the thermo-fluid field inside the furnace, which aims to have a deeper understanding of the field and thus provides a reference for the design of the furnace. The characteristics of the thermo-fluid field were investigated by changing the way of torch arrangement. Spiralling flows are generated inside the furnace when the rotary-angle is greater than 0 °. The upward and downward flows are strongly mixed at their interface, which is conducive to the interaction between them. Besides, the large-scale recirculation, formed in the cases where the rotary-cutting angle is larger than 0 °, can greatly increase the residence time and temperature of the product gases produced from the medical waste, which is beneficial to the complete decomposition of harmful substances.

For the case where the rotary-cutting angle is 0 °, the thermal plasma jets converged in the central area of the molten pool, resulting in severe thermal shocks to the furnace throat, which greatly shortens the life of the furnace. For the case where the rotary-cutting angle is larger than 0 °, the spiral flow drives the thermal plasma jets to flow upward spirally, which avoids the local temperature to rise sharply. Besides, when an appropriate rotary-cutting angle is adopted, a more uniform temperature distribution inside the furnace can be achieved, which is beneficial to complete decomposition of the medical waste.

References
[1] Yujun Wei, Meng Cui, Zhonghua Ye, Qingjun Guo (2021) Environmental challenges from the increasing medical waste since SARS outbreak. Journal of Cleaner Production 291(125246):1-12.
[2] Mochammad Chaerul, Masaru Tanaka, Ashok V Shekdar (2008) A system dynamics approach for hospital waste management. Waste Management 28(2):442-9.
[3] Ahmed Arafa, Ehab S Eahak (2020) Medical waste handling and hepatitis B virus infection: A meta-analysis. American Journal of Infection Control 48(3):316-9.
[4] Nema S K, Ganeshprasad K S (2002) Plasma pyrolysis of medical waste. Current science 83(3):271-8.
[5] Xiaowei Cai, Du Changming (2021) Thermal Plasma Treatment of Medical Waste. Plasma Chemistry and Plasma Processing 41(1):1-46.
[6] Paul Breeze (2018) Energy from Waste. London: Academic Press.
[7] M Punčochř, B Ruj, P K Chatterj (2012) Development of Process for Disposal of Plastic Waste Using Plasma Pyrolysis Technology and Option for Energy Recovery. Procedia Engineering 42:420-30.

[8] Dave Pn, Joshi Ak (2010) Plasma pyrolysis and gasification of plastics waste—a review. Journal of Scientific and Industrial Research 69(3):177-9.

[9] Fabry, Frédéric ; Rehmet, Christophe ; Rohani, Vandad ; Fulcheri, Laurent (2013) Waste Gasification by Thermal Plasma: A Review. Waste and Biomass Valorization 4:421-39.

[10] Janajreh Isam, Raza Syed Shabbar, Valmundsson Arnar Snaer (2013) Plasma gasification process: Modeling, simulation and comparison with conventional air gasification. Energy Conversion and Management 65:801-9.

[11] Moustakas K, Xydis G, Malamis S, Haralambous K.-J, Loizidou M (2008) Analysis of results from the operation of a pilot plasma gasification/vitrification unit for optimizing its performance. Journal of hazardous materials 151(2):473-80.

[12] Gomez E, Rani D Amutha, Cheeseman C R, Deegan D, Wise M, Bocccacini A R (2009) Thermal plasma technology for the treatment of wastes: a critical review. J Hazard Mater 161(2):614-26.

[13] Park Hs, Lee B J, Kim S J (2005) Medical waste treatment using plasma. Journal of Industrial and Engineering Chemistry 11(3):353-60.

[14] Zeng Jiachen, Yue Yang, Gao Qi, Zhang Jia, Zhou Jizhi, Pan Yun, et al (2019) Co-treatment of hazardous wastes by the thermal plasma to produce an effective catalyst. J Clean Prod 208:243-51.

[15] Chu J P, Hwang I J, Tzeng C C, Kuo Y Y, Yu Y J (1998) Characterization of vitrified slag from mixed medical waste surrogates treated by a thermal plasma system. Journal of Hazardous Materials 58:179-94.

[16] H Sheng, R Wang, Y Xu, Y Li, J Tian (2008) AC plasma arc system for pyrolysis of medical waste and pops. 27th annual international conference on thermal treatment technologies. Montreal, Quebec, Canada. 605-12.

[17] Zhovtyansky Victor A, Petrov Stanislav V, Lelyukh Yuriy I, Nevzglyad Igor O, Goncharuk Yuriy A (2013) Efficiency of renewable organic raw materials conversion using plasma technology. IEEE Trans Plasma Sci 41(12):3233-9.

[18] Cedzynska K, Kolacinski Z, Izydorczyk M, Sroczynski W (1999) Plasma vitrification of waste incinerator ashes. Proceedings of the 1999 International Ash Utilization Symposium, F.

[19] Spores R, Pfender E (1989) Flow Structure of A Turbulent Thermal Plasma Jet. Surface and Coatings Technology 37(3):251-70.

[20] John W Mckelliget, G T Massachusetts, Ernesto Gutierrez Miravete, Michael Cybulsky (1998) An Integrated Mathematical Model of the Plasma Spraying Process. Proceedings of the 15th International Thermal Spray Conference. Nice, France.

[21] Gleizes Alain (2015) Perspectives on Thermal Plasma Modelling. Plasma Chem Plasma Process 35:455-69.

[22] ANSYS I. ANSYS Fluent Theory Guide (2018) Lebanon, NH.