Numerical Simulation Optimization and Experimental Study of Vacuum Ultraviolet Solution Equipment Based on CFD Technology

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Abstract. In order to improve the photo-degradation efficiency of waste gas and the utilization rate of ultraviolet lamp, numerical simulation software was used to simulate the wind speed field in ultraviolet equipment. The simulation of uniform and dislocation arrangement of ultraviolet lamp in ultraviolet equipment, taper of variable diameter of equipment, transverse flow and cis flow of ultraviolet equipment is presented. The results show that the gas flow in the equipment is more uniform than that in the ultraviolet lamp. The reducing taper of ultraviolet equipment becomes smaller, and the gas retention area gradually becomes smaller. When the reducing taper is reduced to 30\(^\circ\), it is most suitable. The wind speed field in the downstream ultraviolet equipment is more uniform than that in the horizontal flow type, and the ultraviolet utilization rate is higher. In addition, the tubular downstream ultraviolet equipment can not only ensure the utilization rate of ultraviolet lamp, but also improve the degradation effect of organic waste gas.

1. Introduction

With the development of economy, the problem of environmental pollution is more and more serious. Volatile organic compounds (VOCs) are toxic and highly carcinogenic, causing harm to the environment and human body [1]. For low concentration of volatile organic compounds (VOCs), UV degradation technology has the advantages of high treatment efficiency and low operating and maintenance cost. There are two kinds of ultraviolet photolysis pathways: one is direct photolysis, the other is photo-oxidation. For example, under 185nm ultraviolet wavelength radiation, toluene can directly demethylation or direct ring opening [2], chlorine atoms in chlorobenzene can be directly removed [3]. Photo-catalytic oxidation is a hot topic in the study of ultraviolet degradation of organic compounds. However, there is little research on the simulation optimization of UV degradation equipment.

The design of photo-degradation of organic waste gas is complex, and many factors need to be considered comprehensively. By improving the flow field uniformity of organic waste gas in the vacuum
ultraviolet equipment, increasing the residence time between organic waste gas and the ultraviolet lamp and increasing the light utilization rate of the ultraviolet lamp, the degradation efficiency of vacuum ultraviolet can be effectively improved, and the number of ultraviolet lamps used can be reduced to save costs [4]. CFD (computational fluid dynamics) is a kind of numerical simulation software that simulates fluid flow field and other parameters by controlling relevant basic equations [5-11]. Compared with traditional experimental methods, CFD simulation is economical, efficient and the results are vivid and intuitive. Therefore, CFD numerical simulation was used to visually analyze the flow field distribution in the reaction vacuum ultraviolet reactor, so as to optimize the design of the reactor.

2. Model building

Combined with the engineering practice, this study simulates and optimizes the photo-degradation reactor applied in the engineering. In the vacuum ultraviolet equipment, whether the exhaust gas flows uniformly through the reactor has a great impact on the utilization rate of the ultraviolet lamp, which directly affects the photo-degradation efficiency of the exhaust gas and the utilization rate of the ultraviolet lamp. Therefore, this study only focuses on the components related to the exhaust gas flow field, and focuses on the influence of different diameter-varying angles, lamp arrangement ways and lamp arrangement directions on the flow field of vacuum ultraviolet equipment.

2.1. Research object

At present, there are two ways of ultraviolet lamp arrangement according to the direction of ultraviolet lamp arrangement in both waste gas and waste water treatment engineering applications: cross-flow and downstream flow [12]. Cross-flow type, that is, the flow direction of waste gas or waste water is perpendicular to the direction of UV lamp placement. Fig.1 and Fig.2 are both cross-flow type arrangements. Downstream, that is, the direction of UV distribution is parallel to the direction of the flow of waste gas or water.

| The physical model                        | The name                                              | Parameters size | unit |
|------------------------------------------|-------------------------------------------------------|-----------------|------|
| Cross flow vacuum UV reactor             | Ultraviolet lamp length                               | 540             | mm   |
|                                          | Ultraviolet lamp diameter                            | 19              | mm   |
|                                          | Center spacing of ultraviolet lamp (the lamp tubes are arranged neatly) | 100             | mm   |
|                                          | UV lamp left center spacing (the lamp tubes are arranged neatly) | 130             | mm   |
|                                          | Center spacing of ultraviolet lamps (dislocated arrangement of lamp tube) | 164             | mm   |
|                                          | Reaction length                                       | 560             | mm   |
|                                          | Reaction device width                                 | 500             | mm   |
|                                          | Reaction equipment height                             | 425             | mm   |
|                                          | Inlet and outlet pipe diameter                        | 300             | mm   |
|                                          | 30° inlet flaring length                              | 190             | mm   |
|                                          | 30° outlet contraction port length                    | 190             | mm   |
|                                          | 45° inlet flaring length                              | 100             | mm   |
|                                          | 45° outlet contraction port length                    | 100             | mm   |
|                                          | 60° inlet flaring length                              | 58              | mm   |
|                                          | 60° outlet contraction port length                    | 58              | mm   |
Figure 1. Transverse flow vacuum ultraviolet reaction device (lamp tubes arranged neatly)

Figure 2. Transverse flow vacuum ultraviolet reaction device (lamp dislocated arrangement)

Table 2. Physical model geometry of downstream vacuum ultraviolet reactor

| The physical model                        | The name                          | Parameters | size | unit |
|------------------------------------------|-----------------------------------|------------|------|------|
| Parallel flow lamp distribution reactor  | Ultraviolet lamp length           | 540        | mm   |      |
|                                           | Ultraviolet lamp diameter         | 19         | mm   |      |
|                                           | UV lamp left center spacing       | 130        | mm   |      |
|                                           | Center spacing of ultraviolet lamp| 170        | mm   |      |
|                                           | Reaction length                   | 560        | mm   |      |
|                                           | Reaction device width             | 500        | mm   |      |
|                                           | Reaction equipment height         | 425        | mm   |      |
|                                           | Inlet and outlet pipe diameter    | 300        | mm   |      |
|                                           | 30°inlet flaring length           | 190        | mm   |      |
|                                           | 30°outlet contraction port length | 190        | mm   |      |

Figure 3. Forward flow vacuum ultraviolet reaction device

Figure 4. Cylindrical vacuum ultraviolet reaction device
2.2. Basic assumptions and boundary conditions

In this study, considering that the waste gas stays in the vacuum ultraviolet equipment for a short time and flows through a short distance, the flow in the flow field is a single-phase flow, so the heat transfer in the system is not considered. The change of gas volume caused by photochemical reaction and organic degradation is not considered. Regardless of the existence of particulate matter in the actual working condition, the organic waste gas is regarded as normal temperature air and meets the ideal gas state. It is assumed that the exhaust gas is a turbulent fluid flowing steady-state in a vacuum ultraviolet reactor. In this study, the boundary conditions were set as inlet wind speed of 0.34 m/s, outlet static pressure of 0, and temperature of 298K.

2.3. Governing equation and solution method setting

Unsteady state continuity equation:
\[ \frac{\partial \rho}{\partial t} + \text{div}(\rho U) = 0 \] (1)

Momentum conservation equation:
\[ \frac{\partial (\rho u)}{\partial t} + \text{div}(\rho u U) = \text{div}(\mu \text{grad} u) - \frac{\partial p}{\partial x} + S_u \] (2)

\[ \frac{\partial (\rho v)}{\partial t} + \text{div}(\rho v U) = \text{div}(\mu \text{grad} v) - \frac{\partial p}{\partial y} + S_v \] (3)

\[ \frac{\partial (\rho w)}{\partial t} + \text{div}(\rho w U) = \text{div}(\mu \text{grad} w) - \frac{\partial p}{\partial z} + S_w \] (4)

Energy conservation equation:
\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial u} + \frac{\partial (\rho v)}{\partial v} + \frac{\partial (\rho w)}{\partial w} = 0 \] (5)

u, v and w are velocity vectors in the X, Y and Z directions, and the units are m/s

Su, Sv, Sw is the source term. P is the static pressure.

In this simulation study, considering the actual conditions in the laboratory and the setting conditions during grid division, the SIMPLE pressure-velocity coupling equation is selected. The pressure is in second-order discrete format, and the momentum is in second-order upwind format for simulation. Solving the model selection of RNG k - factor model.

2.4. Mesh generation

The model in this study USES mesh software in workbench to automatically divide the mesh. Will choose in the grid size of advanced engineering proximity and curvature, choose fine correlation center, other is set to the default Settings. After the meshing, check the meshing quality to ensure that the mesh volume is positive. The mesh results are shown in Fig.5.
Grid division of ultraviolet equipment with taper of variable diameter of 30° (orderly arrangement of lamp tubes)

The reduced taper is 90° horizontal flow UV equipment grid diagram

Grid diagram of UV equipment with taper of 60° horizontal flow

Grid diagram of UV equipment with reduced taper 45° cross flow

Grid diagram of UV equipment with taper of variable diameter of 30°

The reduced taper is 30° downstream ultraviolet equipment grid division diagram

The reduced taper is 30° cylindrical downstream ultraviolet equipment grid diagram

Figure 5. Meshing results

3. Simulation results and analysis
In order to intuitively observe the flow field of exhaust gas in the vacuum ultraviolet reactor, the numerical simulation results are presented in the form of cloud image, and the color change in the cloud image represents the change of wind speed in the space. According to the actual machining Angle standard, the taper of reduced diameter is selected to be 90°, 60°, 45° and 30°.
Figure 6. Internal velocity cloud diagram of cross-flow ultraviolet equipment with variable diameter taper of 30° (orderly arrangement of lamp tubes)

Fig.6 shows the xOz profile cloud map (left) and xOy profile cloud map (right), respectively. From Fig.6, it can be observed that the first row of ultraviolet lamps at the inlet end has obvious phenomenon of winding around the column, and there is airflow vortex formation. In order to improve the above problems, we designed a downstream UV equipment with UV lamp dislocation arrangement.

Figure 7. Internal velocity cloud diagram of cross-flow ultraviolet equipment with variable diameter taper of 90°

Figure 8. Internal velocity cloud diagram of cross-flow ultraviolet equipment with variable diameter taper of 60°

Figure 9. Internal velocity cloud diagram of cross-flow ultraviolet equipment with variable diameter taper of 45°

Figure 10. Internal velocity cloud diagram of cross-flow ultraviolet equipment with variable diameter taper of 30° (lamp misplacement)

By comparing Fig.7-10, we find that the retention area gets smaller when the taper gets smaller. By comparison with Fig.6, the dislocated arrangement of the lamp tube makes the flow rate of the ultraviolet lamp very uniform in the upper and lower regions and the left and right regions. However, the gas in cross-flow ultraviolet equipment has the phenomenon of flow around. Therefore, we designed the downstream ultraviolet equipment (Fig.11).
As can be seen from Fig.11, when the diameter accuracy is 30°, compared with the cross-flow ultraviolet equipment, the velocity cloud images in the xOz profile and xOy profile have no detention area. In the area where the vacuum ultraviolet energy radiates to, the gas flows evenly because there is no flow around, so the ultraviolet lamp is fully utilized.

Considering that ultraviolet radiation from ultraviolet lamp is cylindrical, in order to ensure the efficient use of ultraviolet lamp, and to take into account the treatment effect of organic waste gas, further optimize the design of downstream ultraviolet equipment, a cylindrical downstream ultraviolet equipment was designed. As can be seen from Fig.12 and Fig.13, the flow field in the tubular downstream ultraviolet equipment is very uniform. The greatest advantage of cylindrical ultraviolet equipment is the high ultraviolet utilization rate.

4. Experimental research

4.1. Vacuum UV degradation reactor

The reactor for photo-oxidation degradation of toluene includes inlet diameter change, UV reaction zone and outlet diameter change, inlet diameter change of 10mm, taper change of 25°, and inlet and outlet diameter change are relative. The UV reactor is a stainless steel cylindrical reactor with an inner diameter of 150mm and a height of 180mm. The effective radiation volume of the vacuum ultraviolet device is 2.7L, and three vacuum ultraviolet low-pressure mercury lamps are placed in the reactor. Three low pressure mercury lamps are placed in an equilateral triangle at the center of the reactor.
4.2. Experimental results

Relevant experiments were carried out with the optimized equipment. Toluene, a typical benzene series in volatile organic compounds, was selected as the target pollutant. The results showed that when the relative humidity was 60.5%, the residence time was 5s, the ultraviolet lamp power was 54W, and the initial concentration of toluene was 19.25mg/m3, the corresponding degradation efficiency of toluene was 92.85%. Compared with the general traditional equipment, it has obvious advantages.

5. Conclusion

In this study, numerical simulation software is used to simulate the wind speed field in ultraviolet equipment. The following conclusions are drawn: 1. The dislocation arrangement ratio of ultraviolet lamp tube is conducive to the uniform gas passage in the equipment. 2. The reduced taper of ultraviolet equipment has a great influence on the wind speed field inside the equipment. As the taper gets smaller, the retention area gets smaller. 3. Compared with the horizontal flow type, the internal wind speed field of the direct flow type ultraviolet equipment is more uniform and the ultraviolet utilization rate is higher. 4. Tubular downstream ultraviolet equipment can not only ensure the utilization rate of ultraviolet lamp, but also improve the degradation effect of organic waste gas.

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