Numerical simulation of elimination of white smoke in coal-fired power plants with WFGD system

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Abstract. White smoke discharged from chimney in coal-fired power plants always includes residual sulfide which can cause corrosive damage to buildings and environment around. In most coal-fired power plants, there are three major measures to eliminate white smoke: direct heating, condensing and heating, mixing with dry flue gas at high temperature. Main studies on white smoke elimination treat diffusion process as simple mixing of smoke and atmosphere, which has large deviation from reality. By 3D-modeling and numerical simulation, accurate data of white smoke elimination process is obtained. Simulation results indicate that humidity and temperature of atmosphere as well as smoke gas temperature are influential factors to the formation of white smoke. A fitting formula of atmosphere temperature, smoke gas discharge temperature and humidity has analyzed from simulation results, which provides exact data reference for practical white smoke elimination in coal-fired power plants.

1. Introduction

At present, most coal-fired power plants with capacity above 300MW utilizes install wet flue gas desulfurization (WFGD) system to desulfurize flue gas [1]. Although this technology has been well developed for decades, 100% desulfurization efficiency is still hard to be realized. As policies related to pollution emission becoming more and more stringent, concentration of sulfur dioxide discharged from power plant chimney have to keep lower than 35mg/m3 in China [2]. Therefore, water vapor is the major component of smoke gas with minor sulfide. When high temperature smoke gas including sulfide is emitted into atmosphere, vapor will be cooled and condensed into droplets containing sulfuric acid [3], which causes corrosive damage to buildings and nature environment around coal-fired power plants, especially in the downwind area. According to scattering theory, water droplets are visible under sunlight, which is white smoke known by the public. Since the white smoke brings about environment disruption and visual pollution, coal-fired power plants have responsibility to eliminate it.

Up to now, major theoretical studies on white smoke elimination use “straight line method” [4] which determines treatment process by making a tangent line of saturated air line through ambient state point [5] on pressure-temperature diagram. However, in practice, diffusion process of flue gas closely relates to ambient temperature, humidity, wind speed and the state of smoke gas itself. In this study, a 3D model of chimney and ambiance is built and numerical simulation of flue gas diffusion process is completed. The formation of white smoke is analyzed and measures to eliminate white smoke were compared. Conclusions provide accurate data reference for actual white smoke elimination in power plants.
2. Numerical simulation settings and physical model

2.1. Numerical simulation theories

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to solve and analyze problems that involve fluid flows [6]. In this study, we utilized ICEM CFD of ANSYS for modeling and meshing chimney and ambiance, and then simulated diffusion process by FLUENT.

On the premise that simulate results are corresponding to reality, hypothesizes are made to simplify simulation process. (1) Smoke gas is regarded as ideal gas and impact of impurity in smoke gas is ignored. Components of smoke gas are replaced by mixture of air and water vapor whose physical properties are set according to power plant monitoring data. (2) Real wind is multidirectional at every point. Since it has minor effect on diffusion process, ambiance is simplified as unidirectional flowing air. (3) Since atmospheric pressure has minor influence on condensation process, set the pressure as standard atmospheric pressure at 101325 Pa. In this simulation, six varieties are chosen as temperature, humidity, velocity of smoke gas and air.

The evaporation-condensation model is a mechanistic model which is available with the mixture and Eulerian multiphase models. The liquid-vapor mass transfer is governed by the vapor transport equation,

$$ \frac{\partial}{\partial t} (a \rho_v) + \nabla \cdot (a \rho_v \vec{V}_v) = \dot{m}_{l \rightarrow v} - \dot{m}_{v \rightarrow l} $$

where $v$ is vapor phase, $a$ is vapor volume fraction, $\rho_v$ is vapor density, $\vec{V}_v$ is vapor phase velocity, $\dot{m}_{l \rightarrow v}$ and $\dot{m}_{v \rightarrow l}$ are the rates of mass transfer due to evaporation and condensation, respectively, with units of kg·s⁻¹·m⁻³.

Diffusion process of smoke vapor in air involves species transport. ANSYS FLUENT predicts the local mass fraction of each species, $Y_i$, through the solution of a convection-diffusion equation for the $i$th species. This conservation equation takes following general form:

$$ \frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i $$

where $\vec{J}_i$ is the diffusion flux of species $i$, which arises due to gradients of concentration and temperature.

2.2. Physical model and mesh independence

In the specifications issued by the Chinese power industry, chimney height should be twice higher than buildings near the plant [7]. In this study, the height of chimney is set as 210 m and internal diameter of chimney is 7.4 m. Computational domain is 350 m long in upwind direction, 800 m long in downwind direction and 600 m in height and width. 3D simulation model is showed in figure 1.

![3D simulation model of computational domain](image-url)

Figure 1. 3D simulation model of computational domain
Table 1 describes the boundary setting of simulation model.

| Boundary Type                        | Type setting          |
|--------------------------------------|-----------------------|
| Upwind boundary                      | Velocity inlet        |
| Bottom ground                        | Constant temperature wall |
| Top, side and downwind boundary      | Pressure outlet       |
| Chimney wall                         | Adiabatic wall        |
| Chimney outlet                       | Velocity inlet        |

3. Results and analysis

3.1. Criterion of white smoke formation

The line in figure 2 is called saturated moist air line which shows change of saturated vapor partial pressure and humidity ratio with dry-bulb temperature under standard atmospheric pressure. The linear relation between partial pressure of saturated vapor and humidity ratio follows equation 3,

\[
d = 622 \frac{P_q}{B-P_q}
\]  

where \(d\) is humidity ratio, in unit of g/kg dry air. \(P_q\) is partial pressure of vapor, in unit of Pa. \(B\) is atmosphere pressure, in unit of Pa.

![Figure 2. Saturated moist air line.](image)

When state point of moist air stays under saturated moist air line, all the H\(_2\)O in air exists in gaseous state which is assumed as transparent. When state point of air locates on saturated moist air line, relative humidity of air is 100%. When state point of air is above saturated moist air line, partial pressure of vapor exceeds saturated pressure, which turns vapor into visible white droplets. Therefore, method of white smoke elimination is ensuring state point of smoke gas discharged from chimney under saturated moist air line. Criterion parameter of white smoke formation \(\alpha\) satisfies equation 4,

\[
\alpha = P_q - P_b
\]  

where \(P_q\) is vapor partial pressure of the state point, \(P_b\) is saturated vapor partial pressure corresponding to dry-bulb temperature of the state point. When \(\alpha < 0\), vapor partial pressure of air is smaller than saturated partial pressure, which does not cause white smoke. While \(\alpha > 0\), vapor partial pressure of air is larger than saturated partial pressure, which causes white smoke.

3.2. White smoke formation in different seasons

According to data released from weather bureau of Shandong Province, average atmosphere temperature, relative humidity and wind velocity of different season are obtained and listed in table 2.
Table 2. Atmosphere state parameters in four seasons.

| Season | Spring | Summer | Autumn | Winter |
|--------|--------|--------|--------|--------|
| Atmosphere temperature (°C) | 9 | 28 | 22 | -5 |
| Relative humidity | 50% | 66% | 60% | 65% |
| Wind velocity (m/s) | 3.6 | 2.7 | 2.6 | 2.8 |
| Humidity ratio (g/kg dry air) | 3.6 | 15.5 | 9.8 | 1.7 |

Smoke gas from chimney in power plants equipping with WFGD system is saturated with temperature at 45-55 °C normally. In the simulation case, smoke gas from chimney is set as 50 °C saturated moist air with discharge velocity at 20 m/s. Parameters of atmosphere in computational region are set according to table 1 and conditions of white smoke formation and transformation are obtained by numerical simulation. White smoke formation is analyzed through the value of parameter α. When α grows larger than 0, white smoke gets thicker. Figure 3 shows white smoke distribution on the axis plane of chimney in four seasons, respectively. The figure indicates that the amount of white smoke is light in summer with high temperature and thick in winter with low temperature.

![Figure 3. White smoke distribution on the axis plane of chimney in four seasons.](image)

In order to make more accurate analysis on the change of white smoke, equidistance points are chosen alone movement path of smoke gas from central point of chimney outlet. Figure 4 describes smoke gas states change on central line after discharging from chimney on pressure-temperature diagram. Fitting lines are created according to state points by cubic polynomial. During diffusion, smoke gas states change alone curves with large curvature instead of straight line. White smoke gets thicker after discharging from chimney outlet, then gets lighter and thinner during dilution process until develops to the same state as atmosphere. The difference between partial pressure and saturated partial pressure of vapor is the largest in winter, which causes the thickest white smoke.
Figure 4. States change of smoke gas in different seasons.

3.3. Methods of white smoke elimination

There are three major methods of white smoke elimination. The first way is heating smoke gas directly, which does not change humidity ratio of smoke gas and usually increases energy consumption. The second measure is cooling smoke gas for condensing vapor into droplets and heating the smoke with lesser humidity. The third method is mixing low temperature saturated smoke gas with high temperature dry flue gas, which increases temperature and decreases humidity of smoke gas at the same time. In this study, condensing temperature is set at 45 $^\circ$C for the second method according to power plants practical data. High temperature dry smoke gas in the third method is set at 80 $^\circ$C with humidity ratio at 10 g/kg dry air.

Numerical simulations of methods mentioned above are completed under different atmosphere condition of four seasons. Figure 5 describes elimination process through three methods in spring on pressure-temperature diagram. The results show that in order to eliminate white smoke, gas needs to be heated to 104 $^\circ$C for direct heating and 80 $^\circ$C after condensing at least. For the mixing method, saturated gas should be mixed with at least 47% high temperature dry flue gas. When use “straight line method” to calculate, the process amounts for three methods are 90 $^\circ$C, 70 $^\circ$C and 37%, respectively. By comparison, replacing simulation of diffusion process by the simple “straight line method” causes relatively large error.

Simulations of elimination process under other three seasons are completed. Process amounts are obtained from simulation results and listed in table 3. In spring and winter with low temperature, 50 $^\circ$C saturated smoke gas needs to be overheated 50-150 $^\circ$C, which undoubtedly increases energy consumption of power plants. Condensing and heating method can reduce heat energy and mixing with dry smoke can eliminate white smoke with lower cost.

Figure 5. States change of three elimination methods in spring.
Table 3. The least discharge temperature and mixing fraction in four seasons.

| Elimination method                              | Spring | Summer | Autumn | Winter |
|------------------------------------------------|--------|--------|--------|--------|
| Discharge temperature in direct heating method (°C) | 104    | 56     | 63     | 191    |
| Discharge temperature in condensing and heating method (°C) | 80     | 47     | 52     | 140    |
| Mixing fraction of high temperature dry flue gas    | 47%    | 10%    | 20%    | 67%    |

3.4. Effect of major factors on white smoke formation

Through papers viewing and theoretical analysis, six major influence factors of diffusion process are chosen as temperature, humidity and velocity of atmosphere and smoke gas. Influence extent of factors on the least discharge temperature is obtained by analyzing simulation results, which is: smoke gas outlet velocity < wind velocity < atmosphere relative humidity < smoke gas humidity ratio < atmosphere temperature. According to above analysis, temperature and humidity are two parameters with the greatest impact. For most days in a year of southeast China, wind speed stays smaller than 8m/s, relative humidity keeps beneath 80%. Therefore, 8 m/s of wind speed, 80% of relative humidity and 20 m/s of smoke gas outlet velocity are chosen as fixed value. Through orthogonal method, simulation conditions are determined as five kinds of humidity ratio and 6 kinds of atmosphere temperature. Table 4 shows the least gas discharge temperature under different atmosphere temperature and smoke gas humidity ratio from simulation results.

Table 4. The least discharge temperature (°C) of invisible smoke gas under different conditions.

| Atmosphere temperature (°C) | -5 | 0 | 5 | 10 | 15 | 20 | 25 |
|-----------------------------|----|---|---|----|----|----|----|
| Smoke gas humidity ratio (g/kg dry air) | 40 | 90 | 88 | 70 | 57 | 47 | 40 | 37 |
| 60                          | 135| 125| 102| 82 | 68 | 57 | 48 |
| 80                          | 188| 168| 137| 105| 85 | 71 | 60 |
| 100                         | 238| 211| 170| 130| 103| 84 | 71 |
| 120                         | 300| 255| 202| 155| 120| 96 | 81 |

Figure 6 is fitting surface figure which describes relations among the three variables mentioned above.

By rational function fitting, equation 5 is obtained with fitting parameter R^2=0.99945.
where $x$ is atmosphere temperature, $y$ is smoke gas humidity ratio, $z$ is the least discharge temperature of invisible smoke. When atmosphere temperature is known, relation between discharge temperature and smoke humidity as well as process amount of three elimination methods can be calculated by equation 5.

4. Conclusion
There are three major white smoke elimination measures which are direct heating, condensing and heating, mixing with high temperature dry flue gas. Among them, mixing with dry flue gas is simple and energy-saving by comparison. The numerical simulation results under practical conditions indicate that “straight line method” has large error. Therefore, results obtained by simulation and analysis in this study are more accurate. By single variable method, effect degree ranking of six variables is obtained, which is: smoke gas outlet velocity $<$ wind velocity $<$ atmosphere relative humidity $<$ smoke gas humidity ratio $<$ atmosphere temperature. Through orthogonal method of simulation, fitting equation of atmosphere temperature, smoke gas humidity and the least discharge temperature is obtained, which provides accurate reference for white smoke elimination in power plants.

Acknowledgments
I am grateful for the support of Industrial Ecology Institution in Shandong University. I would like to show my deepest gratitude to my supervisor, Pro. Luan Tao who provide this research projects with valuable guidance and financial support.

References
[1] You, L., Carlos, E.R., Joshua, C., Kayla, A.P., Robert, W.W. (2019) Developing steady and dynamic ORP models for mercury emissions control in power plants using WFGD operating data. Fuel, 235: 54-62.
[2] Zhao, X., Deng, C., Huang, X., Kwan, M-P. (2017) Driving forces and the spatial patterns of industrial sulfur dioxide discharge in China. Science of The Total Environment, 577: 279-288.
[3] Mahinsasa, R., Parnthep, J., Somnuk, T., Pisanu, T. (2018) Utilization of coal fly ash and bottom ash as solid sorbents for sulfur dioxide reduction from coal fired power plant: Life cycle assessment and applications. Journal of Cleaner Production, 202: 934-945.
[4] Tian, D., Shu, W., Xiao, X., Ming, Z. (2017) Eliminating the effects of refractive indices for both white smokes and black smokes in optical fire detector. Sensors and Actuators B: Chemical, 253: 187-195.
[5] Ma, S., Chai, J., Jiao, K., Ma, L., Zhu, S., Wu, K. (2017) Environmental influence and countermeasures for high humidity flue gas discharging from power plants. Renewable and Sustainable Energy Reviews, 73: 225-235.
[6] Toparlar, Y., Blocken, B., Matheu, B., Van, H.G.J.F. (2017) A review on the CFD analysis of urban microclimate. Renewable and Sustainable Energy Reviews, 80: 1613-1640.
[7] Liang, S., Yang, W., Song, J., Wang, L., H, G. (2018) Wind-induced responses of a tall chimney by aeroelastic wind tunnel test using a continuous model. Engineering Structures, 176: 871-880.