Simulation study on the relationship between catalyst particle concentration and flow field of a gas turbine

Guangkui Liu\textsuperscript{1*}, Sicong Sun\textsuperscript{1}, Long Sha\textsuperscript{2}, Kui Liang\textsuperscript{1}, Xisheng Yang\textsuperscript{1}, Dong An\textsuperscript{1} and Qi Wen\textsuperscript{1}

\textsuperscript{1}Chinese Special Equipment Inspection & Research Institute
\textsuperscript{2}Shenyang Blower Works Group Corporation

E-mail: liuguangkui9527@163.com

Abstract. In this paper, the characteristics of the flow field in the gas turbine under different catalyst particle concentrations are simulated and analyzed by FLUENT software. The influences of catalyst particle concentration on the high-temperature smoke flow field, the movement track of catalyst particles and the erosion of the moving blade are studied in detail. The results show that the change of particle concentration has no obvious influence on the high temperature smoke flow field. The erosion wear of moving blade mainly occurs near the leading edge and trailing edge of the blade. The possibility of erosion wear at the leading edge is obviously greater than that at the trailing edge. The concentration of catalyst particles has a great influence on the erosion wear of moving blade. The erosion wear will be aggravated with the increase of catalyst particle concentration.

1. Introduction

The flue gas turbine is the main energy recovery equipment in the heavy oil catalytic cracking unit\cite{1, 2}. The flue gas turbine generally works long hours under a high speed of 6000-7000r/min, 600~700$^\circ$C and 0.2Mpa\cite{3, 4}. When the catalyst separation effect is poor, a considerable number of catalyst particles are attached into the flue gas, which will cause serious erosion to the moving blade. The blade erosion wear of the smoke turbine is a typical gas-solid erosion wear\cite{5, 6}. The high-temperature flue gas with solid catalyst particles enters into the smoke turbine and moves rapidly in the flow passage between the stationary blade and moving blade. They collide and impact the smoke turbine blade, which results in blade wear\cite{7}.

Many scholars have carried out numerical simulation research on gas turbine flow\cite{8-10}. Du et al.\cite{11} studied the distribution of the distribution of gaseous phase flow field in flue gas turbines by using a CFD-based numerical simulation method. The results showed that the fine catalyst particles entrained by exhaust gases more readily accumulate and melt on the pressure surface of blades. Tan et al.\cite{12} studied the numerical simulations of gas-solid two-phase flow in the flue gas turbine stage.
cascade for FCC based on Euler-Lagrange model. The results showed that the impact erosion at top of blade trailing edge is caused by the particles no smaller than 10μm. Dong et al.[13] used the finite element software ANSYS/LS-DYNA to study the fatigue fracture of flue gas turbine blade caused by the erosion and abrasion of the solid catalyst particles. The erosion rule on the target material with the same particle size and different impact velocity as well as the erosion effect on the different size particles were gotten. It can be seen that larger particles will have erosion wear on the turbine blades. The influence of particle concentration on the flow field and dynamic blade erosion in the turbine needs to be further investigated. Therefore, in order to study the influences of catalyst particle concentration on the flow field in the gas turbine, FLUENT software was used in this paper to simulate and analyze the characteristics of the flow field in the gas turbine under different catalyst particle concentrations. The influences of catalyst particle concentration on the high-temperature smoke flow field, the movement track of the catalyst and the erosion of the moving blade were studied in detail. The simulation method and results are described carefully in this paper.

2. Simulation method

2.1. Calculation model

In this paper, the numerical simulation of the internal flow field at the gas turbine was conducted by FLUENT software. The species transport model was selected. The turbulence model was k-ε model. DPM model was used for catalyst simulation. Based on the flow field characteristics in the gas turbine, governing equations were selected as follows:

Conservation of mass equation:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \vec{u}) = 0$$

(1)

Momentum conservation equation:

$$\frac{\partial (\rho \vec{u})}{\partial t} + \text{div}(\rho \vec{u}\vec{u}) = \text{div} (\mu \text{ grad } \vec{u}) - \frac{\partial p}{\partial x} + S_u$$

(2)

$$\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho v\vec{u}) = \text{div} (\mu \text{ grad } v) - \frac{\partial p}{\partial y} + S_v$$

(3)

$$\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho w\vec{u}) = \text{div} (\mu \text{ grad } w) - \frac{\partial p}{\partial z} + S_w$$

(4)

Energy conservation equation:

$$\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho \vec{u} T) = \text{div} (\frac{k}{C_p} \text{ grad } T) + S_T$$

(5)
2.2. **Geometric model and mesh generation**

According to the actual structure of the flue gas turbine, fluid domain geometry model of the flue gas turbine is established. The fluid domain of the flue gas turbine consists of inlet section, stator blade, moving blade and outlet section, which contained 38 stator blades and 57 moving blades. The actual structure of the flue gas turbine was shown in Figure 1. The geometric model of numerical simulation was shown in Figure 2.

![Figure 1. Structure diagram of the smoke turbine](image)

![Figure 2. Fluid domain model of the flue gas turbine](image)

The Mesh module in ANSYS was used to divide the geometric model. In this paper,
tetrahedral unstructured grids were used and the number of grid nodes in the computational domain was 15.7 million. The Mesh division result of the geometric model was shown in Figure 3.

Figure 3. Mesh generation results of the geometric model

2.3. Boundary conditions and working condition arrangement
This study used a Density-Based Solver (a dense-based Solver that can achieve high computational accuracy) for numerical simulation. The solution method was implicit (implicit). The working medium is high-temperature flue gas. The inlet temperature of the flue gas is 670 °C. The rotor speed of the flue gas turbine is 6263 r/min. The flue gas flow is 1796.0 Nm³/min under rated conditions. The specific simulation parameters and conditions were shown in Table 1.

|                | High-temperature flue gas traffic [Nm³/min] | High-temperature flue gas inlet temperature [K] | Gas turbine speed [r/min] | Catalyst particle concentration [g/m³] | Catalyst particle size [m] |
|----------------|---------------------------------------------|-----------------------------------------------|---------------------------|---------------------------------------|---------------------------|
| M_1            | 1796.0                                      | 943.0                                         | 6263                      | 0.2                                   | 1.5×10⁻⁶                   |
| M_2            | 1796.0                                      | 943.0                                         | 6263                      | 0.17                                  | 1.5×10⁻⁶                   |
| M_3            | 1796.0                                      | 943.0                                         | 6263                      | 0.13                                  | 1.5×10⁻⁶                   |
| M_4            | 1796.0                                      | 943.0                                         | 6263                      | 0.09                                  | 1.5×10⁻⁶                   |

3. Simulation results and analysis
3.1. Influence of catalyst particle concentration on smoke flow field at high temperature
Figures 4(a)–(d) show the pressure distribution cloud map of blade median diameter (50% blade height) at different particle concentrations. It can be seen that the pressure
of high-temperature flue gas decreases gradually along the flow direction. There is no obvious difference between the calculated pressure value and the change of pressure gradient when the catalyst particle concentration changes. Simultaneously, at the moving blade work and non-work face, the change trend and the velocity distribution pattern of the pressure distribution along the blade shape, each moving blade high pressure distribution curve of the line, temperature of the flow field and temperature gradient did not change obviously with the concentration of the catalyst particles. The reason is that the flow field particle concentration level was low, which can't have obvious influence on the momentum and thermodynamic characteristics of whole flow field. Therefore, the numerical simulation results show that the pressure distribution of flow field in the gas turbine has no obvious change with changing the concentration of catalyst particles.

3.2. Influence of the concentration of catalyst particles on the trajectory of the catalyst

Figures 5(a)–(d) show the particle movement trajectory at the rotor blade under different catalyst particle concentrations. As can be seen from the figure, there is no obvious difference in the movement trajectory of catalyst particles with the change of particle concentration. The catalyst particles impinged on the moving blade under the
action of different factors such as the turbulent action of high temperature flue gas, inertia force and thermal swimming force. When the catalyst particles are accelerated through static blades, they impact the rotor blades at a high speed. When they collide with the rotor blades, their velocity decreases. After collision and reflection, the catalyst particles accelerate away from the rotor blades with the high-temperature flue gas. Numerical simulation shows that the erosion positions of rotor blades are different at different catalyst concentrations, but most of the erosion occurs near the leading edge and trailing edge of the blades.

![Image](image1)

(a) M_1  
(b) M_2  
(c) M_3  
(d) M_4  

**Figure 5.** Influence of different catalyst particle concentrations on particle trajectory

3.3. **Influence of catalyst particle concentration on dynamic blade erosion**  
Figures 6(a)–(d) show the axial distribution of particle erosion wear on moving blade when the catalyst particle concentration is changed. Numerical simulation results show that the change of catalyst concentration has a great influence on the erosion and wear of rotor blades. With the decrease of catalyst concentration, the axial erosion rate of the moving blade decreased to different degrees. The erosion wear mainly occurred in the leading edge and trailing edge of the moving blade as well. The erosion wear of the leading edge of the blade was much greater than that of the trailing edge. With the increase of catalyst particle concentration, the erosion and wear in the middle of the blade also increased to different degrees.
Figure 6. Influence of different catalyst particle concentrations on the axial distribution of corrosion wear

4. Conclusion

The influence of catalyst particle concentration on the flow field in the gas turbine was investigated by numerical simulation of the gas-solid two-phase flow field in the gas turbine. The influence of the particle movement trajectory and the erosion of the moving blade were also investigated. Based on the numerical research, theoretical support and guidance are provided for the failure analysis and optimization direction of gas turbine. The specific conclusions of this paper are as follows:

(1) Within the range of catalyst particle concentration studied in this paper, the change of particle concentration will not have a significant impact on the high-temperature smoke flow field.

(2) Moving blade erosion wear mainly occurs near the leading edge and trailing edge of the blade. The possibility of erosion wear at the leading edge is obviously greater than that at the trailing edge.

(3) The catalyst particle concentration has a great influence on the erosion wear of moving blade. With the increase of particle concentration, the erosion wear of moving blade will be intensified to different degrees. Meanwhile, the location of erosion wear of moving blade is also different, but it still mainly occurs near the leading edge and trailing edge of blade.
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