Research on Operation Stability of Standard Orifice Plate in Nuclear Power Plant KME System

Yelei Yin\textsuperscript{1}, Ming Xia\textsuperscript{2}, Xiaolong Wang\textsuperscript{2}, Zhe Yang\textsuperscript{2}

\textsuperscript{1}SuZhou Nuclear Power Research Institute Co., Ltd. Shenzhen, Guangdong, 518124, China
\textsuperscript{2}SuZhou Nuclear Power Research Institute Co., Ltd. Shenzhen, Guangdong, 518124, China

Corresponding author’s e-mail: P196424@cgnpc.com.cn

Abstract. In order to promote the power stability of nuclear power units, the KME thermal balance principle is used to further analyze the factors affecting the flow of the standard orifice plate of the nuclear power plant KME system (Test Instrumentation). The high-accuracy three-coordinate measuring machine is used to detect the arc radius of the entrance edge of the standard orifice plate and the inner diameter of the standard orifice plate. Analysis the operation history data of the standard orifice plate of the nuclear power plant KME system. Study the running radius of the entrance edge of the same orifice plate and the inner diameter of the standard orifice plate under different operating units. Obtain the influence of the arc radius of the entrance edge of the standard orifice plate and the inner diameter of the standard orifice plate of different types of units.

1. Introduction
At present, due to the standard orifice plate in the KME system, the thermal power of the nuclear power unit is unstable. The deviation of the measurement characteristics of the flow orifice plate caused the abnormal decrease in the thermal power of the 17th cycle of the 300,000 kW unit of Qin Shan nuclear power plant\textsuperscript{1}. In addition, during the D209 servicing, a nuclear power plant replaced the old orifice plate. Finally, the unit's electrical power was reduced by about 7MW\textsuperscript{1}.

There are two methods to determine the outflow coefficient of the standard orifice: the geometric inspection method and the coefficient inspection method. The geometric inspection method, also known as dry calibration, these determining the outflow coefficient according to the geometric size of the throttling device and the installation conditions of the throttle device is an advanced method based on the long-term theory and practical experience of the standard throttling device\textsuperscript{2}.

There are three methods for measuring the arc radius of the entrance edge of the standard orifice plate. The first method is the pressure film measurement method, the second method is the touch visual method, and the third method is the CMM scanning measurement method. The die-measuring method need to be compared and estimated, which introduces large errors; the touch visual method only judges by light reflection and cannot be quantified, and the three-dimensional measuring machine scanning measurement method is the most effective. \textsuperscript{3}
2. The effect of standard orifice plate in KME system on unit power

KME system use the heat balance test of the law of conservation of energy, through the second loop to calculate the energy of the primary loop reactor, the enthalpy rise superposition of the three steam generators, thereby calculating the reactor core power [4]. The heat balance of each steam generator is calculated as follows:

\[ W_{SGi} = Q_v H_v + Q_p H_p - W_e H_e \]  

(1)

In formula (1):

- \( W_{SGi} \): the power of each steam generator;
- \( Q_v \): the steam flow rate of the steam generator outlet (kg/s);
- \( H_v \): the steam enthalpy value of the steam generator outlet (kJ/kg);
- \( Q_p \): the steam generator blowdown flow rate (kg/s);
- \( H_p \): the steam generator blowdown enthalpy value (kJ/kg);
- \( Q_e \): the steam generator inlet feedwater flow rate (kg/s);
- \( H_e \): the steam generator inlet feedwater enthalpy value (kJ/kg).

However, there are also heat sources other than the reactor, such as the heat introduced by the reactor main pump, the heat exchanged by the pipeline, etc. Therefore:

\[ W_R = \sum_{i=1}^{3} W_{SGi} - W_{\Delta p_i} \]  

(2)

In formula (2): \( W_R \) is the core power.

According to the KME thermal balance principle, the feed water flow \( Q_e \) at the inlet of the steam generator directly affects the thermal power of the unit.

2.1. Effect of standard orifice plate on KME system flow

Derive the flow equation from the Bernoulli equation and the continuity equation (3):

\[ q_m = \frac{C}{\sqrt{1 - \beta^4}} A_0 \sqrt{\frac{2}{\rho_1}} \Delta p \]  

(3)

In formula (3):

- \( q_m \): mass flow;
- \( \beta = \frac{A_0}{A_1} \); \( A_0 \): orifice opening area; \( A_1 \): pipe cross-sectional area;
- \( C \): outflow coefficient;
- \( \rho_1 \): fluid density;
- \( \Delta p \): differential pressure.

It can be seen from the flow equation that the inner diameter \( d \) of the standard orifice plate and the flow have a square relationship, and its error has a greater influence on the measurement of the flow. According to the standard, the value error should generally be controlled at about \( \pm 0.05\% \). At the same time, the flow rate is also related to the outflow coefficient. From the outflow coefficient equation, the outflow coefficient \( C \) is also related to the standard orifice diameter. The arc radius of the entrance edge of the standard orifice plate is also one of the indexes that affect the outflow coefficient \( C \). If the arc radius of the entrance edge of the standard orifice plate changes, the outflow coefficient needs to be modified correctly [5].

It can be drawn from the flow equation that in addition to the inner diameter and outflow coefficient of the standard orifice plate, factors such as fluid density, differential pressure, and pipe diameter also affect the flow of the KME system.

3. Standard Orifice

“ISO 5167-2-2003”, “JJG 640-2016 Differential Pressure Flowmeters Verification Regulations”, “GB2624.2” all put forward requirements on the arc radius of the entrance edge of the standard orifice: upstream edge \( G \) (orifice entrance edge circle arc radius), no curling and burrs, no burrs visible to the naked eye, and the arc radius \( \text{r}_k \) should not exceed \( \pm 0.0004d \). The axial section of the standard orifice is shown in Figure 1.
Figure 1. Standard orifice plate

Key
E: standard orifice thickness; e: throttle thickness; α: tilt angle; 1: upstream face; 2: downstream face; a: direction of flow.

The installation of the standard orifice plate in the KME system is shown in Figure 2. The main feed water flow flows to the upstream end of the standard orifice plate, and flows out from the inner diameter $d$ to form a jet, thereby forming a differential pressure, which is then monitored by a pressure transmitter, temperature transmitter to calculate the KME system flow. The on-site installation schematic diagram of the KME system standard orifice plate is shown in Figure 2.

3.1. Method for detecting arc radius of entrance edge of standard orifice plate
The detection method of the arc radius of the entrance edge of the standard orifice plate adopts the scanning method of a three-coordinate measuring machine. The scanning method is to divide the inner circle of the standard orifice plate into 8 equal parts, scan and measure 8 places, and set the scanning interval to 5μm. In the fitting method, the maximum inflection point of a single edge of the edge is selected as the extension line of the edge, and the fitting is performed according to the arc, and finally it’s tangent to the extension line of the maximum inflection point \(^6\).
3.2. Method for detecting arc radius of entrance edge of standard orifice plate

According to the requirements of document [2], the detection of the inner diameter of the standard orifice plate should be detected at four substantially equal angle positions, and the average value and relative error of the inner diameter d of the standard orifice plate should be calculated. Therefore, according to the method in [2], this paper divides the standard orifice plate into 8 parts uniformly, collects 8 symmetrical points at the same thickness of the standard orifice plate by a coordinate measuring machine, and evaluates the distance between 4 sets of symmetrical points. Finally, use the result as the measured value of the inner diameter of the orifice plate.

4. Stability of standard orifice plate under different types of units

In consideration of the safe and stable operation and economic benefits of the nuclear power plant, the inspection plan of the standard orifice plate in the KME system is implemented in accordance with the relevant procedures of the overhaul. After several overhauls, the nuclear power plant will uniformly replace the standard flow orifice plates in the KME system. Therefore, due to the limitation of the data discontinuity after replacement, this analysis only analyzes the stability of the same orifice plate under the same pipeline from the standard orifice plate that has not been completely replaced and the standard flow orifice plate is overhauled.

4.1. Stability of arc radius at entrance edge of standard orifice plate

The installation of the standard orifice plate in the KME system and the state of the orifice plate itself will affect the water flow of the steam turbine, which in turn affects the power of the nuclear power unit and the stability of the nuclear power unit. At the same time, once the orifice plate is installed in the on-site pipeline, it cannot be monitored in real time, nor can it accurately grasp the status of the orifice plate. It’s necessary to analyze the $r_k$ status of the same orifice of different types of units under different annual overhauls to determine the operating stability of the standard orifice. The operating results of the arc radius of the entrance edge of the standard orifice plate under different types of units are shown in Table 1.

| unit | Orifice serial number | $r_k$ average value /mm | Relative change absolute value/mm |
|------|-----------------------|-------------------------|----------------------------------|
| Q    | Q1                    | 0.060                   | 0.002                            |
|      |                       | 0.058                   |                                  |
|      | Q2                    | 0.038                   | 0.000                            |
|      |                       | 0.038                   |                                  |
|      | Q3                    | 0.052                   | 0.006                            |
|      |                       | 0.046                   |                                  |
| T    | T1                    | 0.056                   | 0.002                            |
|      |                       | 0.058                   |                                  |
|      | T2                    | 0.068                   | 0.001                            |
|      |                       | 0.069                   |                                  |
|      | T3                    | 0.019                   | 0.017                            |
|      |                       | 0.036                   |                                  |

The steam turbine of unit Q is to increase the exhaust area of the steam turbine, thereby increasing the power of the single machine to produce a half-speed steam turbine, and the steam turbine of unit T is a full-speed steam turbine. Q1, Q2, Q3 are the same standard orifice plate of Q unit under different overhaul. T1, T2, T3 are the same standard orifice plate of T unit under different overhaul.
From the test results in Table 1, the average change of $r_k$ average value of Q1, Q2, Q3, T1, and T2 standard orifice plates under different overhauls is negligible, and it can be considered that the orifice plate has high stability. The average value of $r_k$ of the standard orifice plate in the KME system of the T3 unit under different overhauls is still within ±0.108mm, but the relative change of the average value of $r_k$ has nearly doubled. From this aspect, the stability of the orifice plate is lower. When the standard $r_k$ is larger in the factory, there is a possibility that $r_k$ will be out of tolerance in the next overhaul.

4.2. Standard orifice inner diameter running stability

By measuring the inner diameter of the standard orifice plate, the same orifice plate dismantled for several overhauls of the standard orifice plates of the Q and T units was measured to obtain the inner diameter results of the standard orifice plates of different types of units. The operating status of standard orifice plates under different types of units is shown in Table 2.

Table 2. Stability of inner diameter of standard orifice plate under different types of units

| Unit | Orifice serial number | d average value /mm | Relative change absolute value/mm |
|------|-----------------------|---------------------|----------------------------------|
| Q    | Q1                    | 269.815             | 269.804                          | 0.011 |
|      | Q2                    | 269.840             | 269.839                          | 0.001 |
|      | Q3                    | 269.844             | 269.813                          | 0.031 |
| T    | T1                    | 270.076             | 270.097                          | 0.021 |
|      | T2                    | 269.991             | 269.993                          | 0.002 |
|      | T3                    | 270.017             | 270.012                          | 0.005 |

From the results of Q-unit and T-unit testing in the laboratory, the average change of the average diameter d of the standard orifice plate under different overhauls is very small. The maximum change is 0.031mm, which is a relative change from the theoretical inner diameter of the standard orifice plate of 270mm less than 0.02%, so it can be considered that the inner diameter of the standard orifice plate is relatively stable.

Considering that the temperature of the stable high-temperature fluid in the on-site pipeline is about 220 °C, the linear expansion correction of the inner diameter of the standard orifice plate is also required. The correction formula is as follows:

$$d = d_{20}[1 + \alpha(t - 20)]$$  \hspace{1cm} (4)

In formula (4): $d_{20}$ is the inner diameter of the standard orifice plate at 20°C, $\alpha$ is the expansion coefficient of the standard orifice plate, and $t$ is the on-site temperature.

According to equation (4), under the condition of high temperature in the field of the same standard orifice plate, the measured value of the laboratory and the actual value of the field will be greatly changed, but because the value of $\alpha$ is very small, the same standard orifice plate is more. The relative change of the actual value of the standard orifice inner diameter on site after the overhaul is basically consistent with the relative change measured by the laboratory.
5. Conclusion
The three-coordinate measuring machine is used to detect the arc radius of the entrance edge of the standard orifice plate and the inner diameter of the standard orifice plate, and the stability of the same orifice plate under different operating units with two parameters is studied. It is found that the standard orifice plate $r_0$ of a unit has a large change in the subsequent overhaul, and the standard orifice inner diameters of the two types of units have been smaller and stable after running multiple overhauls. In order to ensure the stable operation of the nuclear power unit, it’s necessary to disassemble and inspect the standard orifice plate in the subsequent overhaul to ensure the reliability of the orifice plate state.

References
[1] Chen ZM, Liao ZJ, Wu XX, et al. (2017) Analysis of the thermal power drop of the 300 million units in Qin Shan Phase I [J]. China Nuclear Power, 10 (2): 228-233.
[2] Sun WQ, Wang JZ. (2005) Design Manual of Flow Measurement and Throttling Device [M]. Chemical Industry Press, Beijing.
[3] Xia M, Nie SB. (2009) Analysis of the method for measuring the angle of the frontal angle of the flow orifice plate [J]. Daya Bay Nuclear Power, (4): 39-43.
[4] Song XN, Xu CR, Chen RF. (2002) Introduction of KME system of Guangdong Lingao Nuclear Power Station [J]. Automation Expo, (6): 39-45.
[5] Sun WQ, Wang JZ. (2005) Design Manual of Flow Measurement and Throttling Device [M]. Chemical Industry Press, Beijing.
[6] Xia M, Zhang DY. (2016) Three-coordinate measuring method of the orifice face-to-face acute angle edge radius and its judging criteria [J]. Daya Bay Nuclear Power, (2): 63-65.
[7] Xia M, Zhang DY. (2016) Three-coordinate measuring method of the orifice face-to-face acute angle edge radius and its judging criteria [J]. Daya Bay Nuclear Power, (2): 63-65.