Development and demonstration of CO\textsubscript{2} flow numerical calibration system – part II

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Abstract. This project takes the flue at the tail of Fujian Kemen Power Generation Company as the research object. Calibration factor, precise flow value, etc. Through the above analysis, it is concluded that the ultrasonic flowmeter has high requirements on the location selection, and the measurement result is closer to the true value. The matrix type flowmeter is easy to arrange, and the location selection sensitivity is low; the single point pitot tube flowmeter has poor accuracy and is not recommended.

1. Introduction
The technical content of this project includes three parts: numerical simulation, field verification and system development. Among them, based on the numerical simulation calculation results, the calibration of multi-form flowmeters is provided, and the correction coefficient is provided. On the basis of this, the accuracy of the on-site verification results are corrected. Combining the results of the two, a CO\textsubscript{2}-based flow value calibration system was developed and used to form a demonstration project. The calibration system should be able to automatically calibrate, automatically generate calibration coefficients and generate reports [1-3].

2. Technical requirements
Some of the numerical calculation methods and processes are: classical fluid mechanics assumes that the fluid motion process and heat transport process satisfy the Navier-Stokes equations. The specific form of the N-S equation system can refer to the fluid mechanics textbook (such as Wu Wangyi's "Fluid Mechanics", published by Peking University Press). Due to the complexity of the internal flow of the flue, considering the magnitude of the Re number, a suitable turbulence model must be adopted in order to simulate the effect of turbulent pulsation on gas momentum and energy transport (ie, Reynolds stress effect). Commonly used turbulence models include SA model, k-e model and k-w model. Taking into account factors such as the amount of calculation, the RNG k-e model or SST k-w model is adopted in this project.

In numerical calculations, in order to ensure better solution accuracy, we can use the second-order format to spatially discretize the RANS equations (Reynolds average N-S equations), and use the SIMPLE series of algorithms to solve the momentum-pressure coupling problem.

In the system development part, the system development part of this project implements the following functions and technologies:
(1) Data interface function: develop a data interface for extracting numerical simulation calculation results, including access functions such as graphics and numerical data;
(2) Data statistics function: to realize basic functions such as access to data statistics and analysis, to generate relevant data curves, plan layout diagrams, statistical charts of measured point deviation values, etc.;

(3) Data optimal plan recommendation: According to the relevant statistical results, provide the optimal plan recommendation. The scheme includes the measurement method, the recommendation of the nearest position of the measuring point, and the calibration coefficient of each position of the measuring point.

(4) For desktop users, develop excellent numerical planning customized interactive environment and visualization functions.

3. Three-dimensional model establishment

According to the above grid, the relevant trial calculation is conducted, and the trial calculation flow rate is 100%, that is, 3600 t/h. The calculation results are as follows. In the model, the wall Y+ value is within the required range, that is, the grid meets the calculation requirements.

![Figure 1. Y+ calculation result](image)

The gas flow in the calculation domain is calculated as an incompressible and steady flow, using the SST k-w turbulence model, and using a full y+ wall treatment in the area near the wall.

For flue gas flow monitoring, there are usually the following methods, each with its own characteristics and applicable methods.

**Table 1. Comparison of main flow velocity monitoring technologies**

| Principle | Pitot tube | Thermal balance flowmeter | Ultrasonic flowmeter | flowmeter Matrix flowmeter |
|-----------|------------|----------------------------|----------------------|---------------------------|
| Measurement method | Pressure difference | Temperature difference | Time difference | Pressure difference |
| Installation method | Point measurement | Point measurement | Line measurement | Area measurement |
| Whether to contact | One side of the flue | One side of the flue | Both sides of the flue | Cross section of the flue |
| Disturbing factors | Dust accumulation, blockage | Dust accumulation, blockage | Probe deposits Dust deposit, blockage | Dust accumulation, blockage |
| Features | Single-point measurement, high intuitive requirements | pure media | line sampling, and the effect of the adsorption of soot on the probe | Accurate calibration, reducing the requirements for single-point straight pipes |
4. Results of numerical analysis of flue

4.1. Analysis of detection method

Calculate the layout of the probe points at 5 cross-sections with different positions. The probe points are arranged according to the Technical Specification for Continuous Monitoring of Flue Gas Emissions from Fixed Pollution Sources (HJ/T 75 -2007). The relevant layout principles are as follows:

![Figure 2. Principles of layout of exploration points](image)

Figure 2. Principles of layout of exploration points

The comparison of the results of the multi-row detection method is as follows. Only one of the 16 detection points showed a large deviation. The measurement results of the remaining 15 points are in the range of 65-140Pa. The mean value of the probe points in the 5 rows is slightly different. The average values of P1-P5 were 86.27, 86.07, 86.97, 89.14, and 93.29, respectively. P1-P3 results are close. It can be seen that after leaving enough space, the deviation of the relevant measurement results is not large.

![Figure 3. Distribution of results of exploration method 2 (100%)](image)

Figure 3. Distribution of results of exploration method 2 (100%)

4.2. Analysis of matrix flowmeter

It can be seen from the results in Section 3.2 that the matrix-based distribution of the average results can effectively avoid single-point measurement deviation. After leaving enough sampling distance, the multi-row results are significantly better than the single-point measurement accuracy. But one of the 16 probe points has a large value deviation.
Figure 4. The location of the maximum deviation point

Figure 4 shows the location of the maximum deviation point. At this point, the value cannot be removed. We examine the deviation value under the arrangement of 16 flow measurement points.

Table 2. Corresponding flow rate and pressure difference value of different flow

| Flow rate (%) | Cross-sectional velocity (m/s) | Theoretical pressure difference (Pa) |
|---------------|-------------------------------|-------------------------------------|
| 20            | 1.898                         | 3.24                                |
| 40            | 3.795                         | 12.97                               |
| 60            | 5.694                         | 29.19                               |
| 80            | 7.59                          | 51.89                               |
| 100           | 9.49                          | 81.09                               |

4.3. Matrix flowmeter results at different flows

Figure 5. Results of matrix differential pressure at different locations (100%)

Figure 3-12 shows the average pressure difference of matrix points at 100%. The theoretical differential pressure value is 81.09Pa, and the differential pressure across the entire detection point is slightly higher than the theoretical differential pressure value.
Figure 6. Results of matrix differential pressure at different locations (80%)
The theoretical pressure difference is 51.89Pa at 80% flow rate.

Figure 7. Differential matrix point pressure difference results (60%)
The theoretical pressure difference at 60% flow is 29.19Pa.

Figure 8. Results of matrix point differential pressure at different locations (40%)
The theoretical pressure difference at 40% flow rate is 12.97Pa.

Figure 9. Differential matrix point pressure difference results (20%)

The theoretical pressure difference at 20% flow is 3.24Pa.

4.4. Analysis of P2 position flow correction coefficient
Based on the calculation results under each flow, the P2 location is selected as the optimal location. Without considering the measurement error of the individual flowmeter, the correction factor is analyzed. The calculation formula for the flow rate of matrix flowmeter is:

\[ V = k \sqrt{\frac{2\Delta P}{\rho}} \]

The maximum and minimum values of the P2 cross-section under different flow rates are as follows:

Figure 10. Comparison of pressure difference of P2 position matrix
Table 3. P2 position correction coefficient table

| Mass Flow (kg/s) | Full load volume flow percentage (%) | Maximum average (Pa) | Minimum average (Pa) | Theoretical value (Pa) | Maximum value Correction factor | Minimum Correction factor | Correction factor | Average correction factor |
|-----------------|--------------------------------------|----------------------|----------------------|------------------------|-------------------------------|---------------------------|----------------------|--------------------------|
| 200             | 22.8                                 | 3.51                 | 3.41                 | 3.24                   | 0.923                         | 0.953                     | 0.938                |
| 400             | 45.7                                 | 13.9                 | 13.55                | 12.97                  | 0.933                         | 0.957                     | 0.938                |
| 600             | 68.5                                 | 31.6                 | 30.7                 | 29.19                  | 0.924                         | 0.951                     | 0.937                |
| 800             | 91.4                                 | 55.67                | 53.13                | 51.89                  | 0.932                         | 0.977                     | 0.951                |
| 1000            | 114.2                                | 86.3                 | 83.01                | 81.09                  | 0.940                         | 0.977                     | 0.961                |

According to the statistical results in the table above, the flow velocity and flow rate calculated at the pressure difference measured at the P2 position are slightly larger than the actual flow rate, and the average correction factor is between 0.937-0.961.

4.5. Analysis of ultrasonic flowmeter

4.5.1. Analysis results. Ultrasonic measurement method adopts line sampling method to measure the flow velocity in the flue, and the flow rate is converted into flow rate for statistics. In order to facilitate the unified comparison method, the pressure difference method is still used for comparison in this calculation. There are 8 groups of ultrasonic flowmeters arranged in this flue, which are installed in four positions. Two sets of 5 pairs of flowmeters are set for each position. A total of 40 ultrasonic flowmeter installation points.

In each pair of flowmeters, the average flow rate on the statistical line sampling method is converted into a differential pressure value.

The specific arrangement of the ultrasonic flowmeter is as follows:

Figure 11. Location of ultrasonic flowmeter
In the figure, the upper two groups are marked as CSB1 and CSB2. The bottom two groups are noted as CSB3 and CSB4. The results of the 4 sets of flowmeters at different flows are as follows:

**Table 4. Ultrasonic flowmeter monitoring results (20%)**

| Group number | CSB1  | CSB2  | Group number | CSB3  | CSB4  |
|--------------|-------|-------|--------------|-------|-------|
| 1            | 3.449 | 3.778 | 1            | 4.262 | 3.609 |
| 2            | 4.029 | 4.301 | 2            | 4.716 | 4.140 |
| 3            | 3.963 | 4.205 | 3            | 3.614 | 3.156 |
| 4            | 3.196 | 3.531 | 4            | 3.248 | 2.778 |
| 5            | 2.593 | 2.936 | 5            | 3.510 | 2.806 |
| **Average**  | 3.446 | 3.750 |              | 3.870 | 3.298 |

**Table 5. Ultrasonic flowmeter monitoring results (40%)**

| Group number | CSB1  | CSB2  | Group number | CSB3  | CSB4  |
|--------------|-------|-------|--------------|-------|-------|
| 1            | 13.904| 14.860| 1            | 17.817| 15.348|
| 2            | 15.349| 15.646| 2            | 19.110| 16.467|
| 3            | 17.337| 18.310| 3            | 14.883| 12.418|
| 4            | 13.219| 15.149| 4            | 13.646| 11.560|
| 5            | 10.466| 11.956| 5            | 14.305| 10.975|
| **Average**  | 14.055| 15.184|              | 15.952| 13.354|

**Table 6. Ultrasonic flowmeter monitoring results (60%)**

| Group number | CSB1  | CSB2  | Group number | CSB3  | CSB4  |
|--------------|-------|-------|--------------|-------|-------|
| 1            | 30.690| 32.980| 1            | 40.626| 34.668|
| 2            | 34.276| 36.195| 2            | 42.365| 36.741|
| 3            | 39.073| 40.933| 3            | 33.358| 27.713|
| 4            | 30.104| 34.370| 4            | 30.970| 26.276|
| 5            | 23.441| 27.029| 5            | 31.076| 23.674|
| **Average**  | 31.517| 34.302|              | 35.679| 29.814|

**Table 7. Ultrasonic flowmeter monitoring results (80%)**

| Group number | CSB1  | CSB2  | Group number | CSB3  | CSB4  |
|--------------|-------|-------|--------------|-------|-------|
| 1            | 57.412| 62.489| 1            | 70.739| 58.775|
| 2            | 61.295| 65.399| 2            | 75.392| 66.186|
| 3            | 68.926| 71.825| 3            | 59.323| 50.274|
| 4            | 53.632| 59.833| 4            | 54.250| 45.366|
| 5            | 41.333| 48.644| 5            | 54.378| 40.945|
| **Average**  | 56.520| 61.638|              | 62.816| 52.309|

**Table 8. Correction coefficient of ultrasonic flowmeter**

| Mass Flow (kg/s) | Flow rate (kg/s) | Theoretical value (Pa) | CSB4 (Pa) | correction factor |
|------------------|------------------|------------------------|-----------|------------------|
| 200              | 22.8             | 3.24                   | 3.298     | 0.982            |
| 400              | 45.7             | 12.97                  | 13.354    | 0.971            |
| 600              | 68.5             | 29.19                  | 29.814    | 0.979            |
| 800              | 91.4             | 51.89                  | 52.309    | 0.992            |
4.5.2. Optimization of installation method

![Figure 12. Location of ultrasonic flowmeter](image)

On this basis, optimize the number of installations and seek the optimal results with fewer installation points. They are divided into single-point measurement, two-point measurement, and four-point measurement. The relevant results are as follows:

1) Single point optimal result

2) Two-point optimal result

Table 9. Ultrasonic flowmeter correction factor (single point)

| Mass Flow (kg/s) | Flow rate (kg/s) | Theoretical value (Pa) | CSB4 (Pa) | correction factor |
|------------------|------------------|------------------------|-----------|------------------|
| 200              | 22.8             | 3.24                   | 3.237     | 1.001            |
| 400              | 45.7             | 12.97                  | 13.086    | 0.991            |
| 600              | 68.5             | 29.19                  | 29.306    | 0.996            |
| 800              | 91.4             | 51.89                  | 53.177    | 0.976            |

The coordinate of the single-point installation position is (7,0,4.25) m, the position is as follows:

![Figure 13. Optimal method for single-point installation](image)
Table 10. Ultrasonic flowmeter correction factor (two points)

| Mass Flow (kg/s) | Flow rate (kg/s) | Theoretical value (Pa) | CSB4 (Pa) | correction factor |
|------------------|------------------|------------------------|----------|------------------|
| 200              | 22.8             | 3.24                   | 3.313    | 0.978            |
| 400              | 45.7             | 12.97                  | 13.519   | 0.959            |
| 600              | 68.5             | 29.19                  | 30.138   | 0.969            |
| 800              | 91.4             | 51.89                  | 54.322   | 0.955            |

The installation coordinates of the two points are
Installation position 1 (7, 0, 4.25) m,
Installation position 2 (7, 6, 0) m, the position is as follows:

![Figure 14. Two-point installation method](image)

3) Four-point optimal result

Table 11. Ultrasonic flowmeter correction coefficient (four points)

| Mass Flow (kg/s) | Flow rate (kg/s) | Theoretical value (Pa) | CSB4 (Pa) | correction factor |
|------------------|------------------|------------------------|----------|------------------|
| 200              | 22.8             | 3.24                   | 3.288    | 0.985            |
| 400              | 45.7             | 12.97                  | 13.432   | 0.966            |
| 600              | 68.5             | 29.19                  | 30.338   | 0.962            |
| 800              | 91.4             | 51.89                  | 53.941   | 0.962            |

Installation position 1 (7, 0, 4.25) m,
Installation position 2 (7, 6, 0) m,
Installation position 3 (7.5, 0, 4.25) m,
Installation position 4 (7.5, 6, 0) m,
The location is as follows:

![Figure 15. The optimal method of four-point installation](image)
5 Summary
CFD calculation is performed for the flue at the tail of Kemen Power Plant. The single point measurement and matrix measurement methods are studied. Based on the above calculations, the following conclusions can be drawn.

1. At a steady flow rate, the flow velocity in the flue fluctuates slightly, but this fluctuation becomes more severe as the flow velocity increases. Affected by the demister, there is a wake or vortex phenomenon in the flow of flue gas after exiting the demister. In this area, the velocity distribution deviation is large. This result determines that the single-point flowmeter used in this flue will result in unstable deviation. It is more difficult to find the best point for single-point measurement in the flue. And the deviation value exceeds the relevant requirements.

2. Leave enough space behind the defogger to arrange 4*4 sets of matrix flowmeters to measure the flow rate is more accurate.

3. Through the study of the layout points of the space, the results of the probe points at 8.42m and 9.42m behind the demister are more accurate.

4. The 9.42m position average value is compared with the theoretical value. The pressure difference measured by the probe point is significantly higher than the actual pressure difference, that is, the flow rate measured by the flowmeter is too large. The coefficient of revision is between 0.937-0.961.

5. Multiple sets of ultrasonic flowmeter probe points are arranged, the position of CSB4 is closest to the theoretical value, and its correction coefficient is between 0.971-0.99. After adding multiple sets of probe points, the correction factor is close to the result of the matrix flowmeter.

6. Based on the above analysis, the ultrasonic flowmeter has high requirements on location selection, and the measurement result is closer to the true value. The matrix flowmeter is easy to arrange, and the position selection sensitivity is low.

The flue gas flow rate of thermal power plants has always been mainly in the form of traditional point measurement and line measurement. The outstanding problems such as poor accuracy and weak representativeness of monitoring data have long existed. The advantages of the above matrix flowmeter in practical applications are obvious. The following part uses the numerical simulation method to calculate the flow of the flue structure at the tail of Kemen Power Plant, extract the internal velocity and pressure distribution to provide the monitoring results of the flowmeter.

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