Research on filed flowrate measuring technology of stack gas for stationary emission source

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Abstract. Under the background of greenhouse gas emission reduction and environmental protection verification becoming a hot spot of social concern, the basic principle and method of filed flowrate measuring technology of stack gas for stationary emission source are introduced in this paper. The key of stack gas flowrate measurement based on velocity-area method is to measure the area of the cross section and the average velocity in the cross section. This paper introduces tow measuring methods of S-pitot tube and multi-path ultrasonic flowmeter. And then, an application of the two measuring methods of stack gas flowrate in a coal-fired power plant in Henan is given. At last, the measuring results of the two methods were analysed and compared, and it was considered that either the S-pitot tube or multi-path ultrasonic flowmeter has a wide application prospect in gas flowrate measurement.

1. Introduction

In recent years, the issue of greenhouse gas emission reduction has aroused wide attention from the international community. At present, there are two methods applied in greenhouse gas emission verification. One is the actual measuring method, which can directly calculate the emission quantity of the greenhouse gas based on the stack gas flowrate and components. The other is the widely used theoretical calculation method, including material balance method and emission factor method, which calculates the emission quantity by accounting the raw materials generating greenhouse gases during the production process and auxiliary production process in industrial enterprises. A large number of experiments shows that more accurate data can be get from the actual measuring method for the stationary emission source. The key technical points of the actual measuring method are the measurement of the stack gas flowrate and the analysis of the components of the gas. This paper will focus on the measuring technology of stack gas flowrate for the stationary emission source.

In the field of stack gas flowrate measurement, the United States is always being in the forefront of the world. The NIST established the flue gas flow standard device in 1990s, and based on it, the NIST carried out the business of flue gas flowmeter calibration. They also researched on the field flowrate measurement method and achieved 5% level of accuracy [1]. Currently, China mainly uses the material balance method and the emission factor method to verify the greenhouse gas emission [2-4]. Although a few stationary pollution emissions are measured by the actual measuring method, but in
most cases these measurements are deficient in the selection of flowmeters and in the distribution of sampling points. Then, because of complex internal disturbance source in the stack or flue, the representativeness of velocity in the actual measurement is usually unsatisfactory, which results in bad accuracy and repeatability of the flowrate data.

2. The principle of the flowrate measurement of stack gas by actual measuring method
The essence of actual measuring method is the velocity-area method in the flow measurement. The flowrate of a cross section can be obtained by multiplying the average flow velocity of all points of the cross section and the area of the cross section. The stack gas has the characteristics of high temperature, high humidity and stuffed with particle impurity, so it is very important for the selection of the flowmeter when measuring the flowrate of stack gas. At present, thermal gas flowmeters, hot-wire anemometers and stack gas ultrasonic flowmeters which are developed in recent years are widely used in the measurement. In the field experiment of stack gas flowrate measurement in the coal-fired power plants, we chose the most widely used S-type pitot tube and the most advanced multi-path ultrasonic flowmeter as the measuring instrument. So, the following will focus on the working principle, the flowrate measuring method and results analysis of the two kinds flowmeters.

3. Field stack gas flowrate measurement using S-type pitot tube method

3.1. Brief introduction of S-type pitot tube
The S-type pitot tube is made by welding two same shape hollow metal tubes together. The structure of S-type pitot is shown in Fig.1. The two hollow metal tubes should be all the same shape and required to open the holes in two directions, and the cross section of the opening is strictly parallel.

![Fig.1. The S-type pitot tube.](image)

In the gas flow velocity measurement, the hole facing the direction of the stack gas coming is recorded as the total pressure hole, and the hole back to the direction of the stack gas is recorded as the static pressure hole. The tail end of the tube is connected to the differential pressure gauge, and the Bernoulli equation can be applied to get the following relation between the velocity of a point in the fluid and the differential pressure.

\[
\Delta p = \frac{2}{\rho} \cdot \frac{2}{C_p} \cdot v
\]

\(\Delta p\), differential pressure between total pressure hole and static pressure hole, pa;  
\(\rho\), density of the measured fluid, kg/m³;  
\(C_p\), Pitot tube coefficient, dimensionless;  
\(v\), gas flow velocity in the S-type pitot position in the stack, m/s.

3.2. Measuring principle of S-type pitot tube method
In order to get the calibration coefficient \(C_p\) of S-type pitot tube, it should be calibrated in the standard testing wind tunnel. It is also necessary to choose the cross section and test points carefully before the measurement of the gas flow velocity. The measuring cross section of pitot tube should be upstream from the spoiler (including bending, necking, expanding the spoiler, visible flame etc.) 8 times of the
equivalent diameter, and be downstream from the spoiler 2 times of the equivalent diameter (hereinafter referred to as the "2-8 principles").

For the stacks compliance with the "2-8 principles", the least number of test points should be in accordance with the following requirements: 1) at least 12 test points should be selected for a stack with the equivalent diameter greater than 0.61m, whether the stack cross section is circular or rectangle; 2) at least 8 test points should be selected for a circular stack with the diameter between 0.30m~0.61m; 3) at least 9 test points should be selected for a rectangle stack with the diameter between 0.30m~0.61m. The distribution of 12 test points in the cross section of the stack (circular or rectangle) is shown in Fig.2.

It is also required there is no large vortex near the selected measuring cross section so as not to affect the measurement results. The "0-degree reference" technique with pitot tube and differential pressure gauge can be used to judge the vortex intensity near each test point in the cross section. After the test, if vortex strength of the cross section is not acceptable, it is necessary to reselect the measuring section or use other techniques to sample the gas flow velocity.

In addition, because of the large humidity of stack gas, the molecular weight of dry gas and wet gas is quite different. So, it is need to convert the molecular weight of dry gas to the molecular weight of wet gas according to formula (2).

\[
M_s = M_d (1 - B_{w/s}) + 18.0 B_{w/s}
\]  \hspace{1cm} (2)

\(M_d\), the relative molecular weight of gas in a stack (calculated basing on dry gas), g/mol;
\(M_s\), the relative molecular weight of gas in a stack (calculated basing on wet gas), g/mol;
\(B_{w/s}\), the content of water vapor in the stack gas, recorded by the percentage of volume, %;

After the molecular weight of the wet gas confirmed, the average gas velocity in the selected cross section can be calculated by the formula (3).

\[
v_s = K_p C_p \sqrt{\frac{\Delta P_{avg}}{P_s M_s}} \frac{T_{(abs)}}{P_s}
\]  \hspace{1cm} (3)

\(v_s\), average flow velocity of all test points, m/s;
\(K_p\), constant in velocity calculation, 34.97 in metric unit, dimensionless;
\(C_p\), Pitot tube coefficient, dimensionless;
\(\Delta P_{avg}\), the average reading of differential pressure meter for all test points in the selected cross section, Pa;
\(T_{(abs)}\), the average absolute temperature of the stack during the measurement, K;
\[ Q = \frac{3600(1 - B_m)\nu A}{\frac{T_{std}}{P_{std}}P} \] (4)

\( Q \), the instantaneous volume flowrate of cross section, m³/h;
\( A \), the area of the selected cross section, m²;
\( T_{std} \), the standard absolute temperature with a value of 293K;
\( P_{std} \), the standard absolute pressure with a value of 760mm Hg.

3.3. Actual measurement

According to the principle of measurement, the emission stack of a gas power plant in Henan has been actually measured. The structural parameters of the stack are as follows: It is cylinder-shaped, and the height of the stack which calculates from the fore-end outlet to the top of the stack is 65.15m. while the radius of the stack is 3.462m; the thickness of the side wall is 0.016m and the ventilation section area is 37.306 m². There are three layers of ring platform outside the stack, which are at the height of 29.3m, 56.3 and 59.6m. In addition, there are three layers and half ring platforms for normal maintenance. The picture of the stack is as shown in Fig.3. When the stack was built, 4 mounting holes were reserved near the bottom of the ring platform, and each hole was 90 degrees apart. This position totally meets the requirement of the "2-8 principle" for the selection of the measuring cross section in the EPA method. In the measuring cross section, 12 test points are distributed according to the requirements, as shown in Fig.2. After determined the measuring cross section, the "0-degree reference" technology was used to do the vortex inspection of the test points, and the results showed that there was no large vortex at each point which meant the position of the measurement cross section was acceptable.

![Fig.3. The picture of a coal-fired power plant stack and the installation of S-type pitot tube and 2*3 paths ultrasonic flowmeter.](image-url)
By analyzing the collected stack gas, the content of the water gas vapor was about 7.3%. The measurement was conducted at three flow velocity points. According to the formula (3), the average flow velocity of all measuring points in the cross section was calculated, which were 7.39 m/s, 15.65 m/s and 35.94 m/s, respectively. After temperature and pressure correction, the flowrate were 82.3745*10^4 m^3/h, 173.1181*10^4 m^3/h and 399.3817*10^4 m^3/h, respectively. When the average velocity was 15.65 m/s, the thermodynamic temperature was 320.73 K and the absolute pressure was 744 mmHg in the measuring section. According to the formula (4), the instantaneous flowrate of the measurement section was 173.1181*10^4 m^3/h. It was found that the readings of differential pressure gauge near the central axis was relatively stable; the closer to the edge of the wall, the smaller the reading was and the more serious the fluctuation was. In this situation, the measurement time should be increased, and the mean value of the readings within a period of time should be taken in the calculation of the average velocity according to formula (3).

3.4. Uncertainty evaluation of flowrate using S-type pitot tube
According to formula (4), the calculation function of the flow velocity of stack gas is given in the form of \( Y = f(X_1, X_2, \ldots, X_N) = c_1X_1^{n_1}X_2^{n_2} \ldots X_N^{n_N} \), so the relative combined standard uncertainty of the flow velocity of stack gas should be given by formula (5).

\[
\frac{\Delta v}{v} = \sqrt{\left(\frac{\Delta c_1}{c_1}\right)^2 + \left(\frac{\Delta n_1}{n_1}\right)^2 + \left(\frac{\Delta X_1}{X_1}\right)^2 + \left(\frac{\Delta X_2}{X_2}\right)^2 + \cdots + \left(\frac{\Delta X_N}{X_N}\right)^2}
\]

\( u(v_i) \), the relative standard uncertainty of flow velocity;
\( u(C_p) \), the relative standard uncertainty of calibration coefficient of S-type pitot tube;
\( u(\Delta p_{avg}) \), the relative standard uncertainty of average value of the readings of differential pressure gauges;
\( u(T_{s(abs)}) \), the relative standard uncertainty of stack gas temperature;
\( u(P_s) \), the relative standard uncertainty of absolute pressure of stack gas in the stack;
\( u(M_s) \), the relative standard uncertainty of molecular weight of wet stack gas in the stack.

According to formula (2), the \( u(M_s) \) is only related to the content of water vapor \( B_{ws} \) (the relative molecular weight of the dry gas in the stack is considered as the stationary value); so it can be rewrite in the form of \( u(M_s) = (18-M_d)u(B_{ws}) \). After field stack gas sampling and chromatograph analysis, the value of \( M_d \) was 29.58, namely \( u(M_d) = 11.58 \). According to the calibration certificate of S-type pitot tube, \( u(C_p) = 0.05\% \), the maximum permissible error of differential pressure gauges was \( \pm 0.1\% \), considering the measured values in the interval submitted to normal distribution, the Type A relative standard uncertainty \( u(\Delta p_{avg})_1 \) was 0.05%; the Type B relative standard uncertainty of repetitiveness of multiple sets of measurements \( u(\Delta p_{avg})_2 \) can be calculated by the Bessel formula of which value was 0.03%; so the \( u(\Delta p_{avg}) = (u(\Delta p_{avg})_1) + (u(\Delta p_{avg})_2) = 0.058\% \). While the relative standard uncertainty of digital thermometer, absolute pressure meter and the content of water vapor was respectively 0.03%, 0.05% and 0.0035%. All those uncertainty components were brought into the formula (5). Finally, the relative standard uncertainty of the flow velocity of stack gas was 0.067%.

While, according to the formula (4), the relative combined standard uncertainty of the flowrate of stack gas can be given by formula (6).

\[
\frac{\Delta Q}{Q} = \sqrt{\left(\frac{\Delta B_{ws}}{B_{ws}}\right)^2 + \left(\frac{\Delta v_i}{v_i}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta T_{s(abs)}}{T_{s(abs)}}\right)^2 + \left(\frac{\Delta P_s}{P_s}\right)^2}
\]

\( u(Q) \), the relative standard uncertainty of flowrate;
\( u(A) \), the relative standard uncertainty of measured cross section area in the stack.

The value of \( u(A) \) depended mainly on the method of radius obtained and the measuring instrument. So, the type B relative standard uncertainty caused by measuring instruments of the steel tape was 0.002% based on the calibration certificate. The combination of uncertainty components is also required to consider the type A relative standard uncertainty caused by the repeated measurements of each parameter during the measurement. All those related uncertainty components were brought into the formula (6). Finally, the relative standard uncertainty of the stack gas flowrate obtained by S-type method was 0.59%.

4. Field stack gas flowrate measurement using multi-path ultrasonic flowmeter method

4.1. Brief introduction of ultrasonic flowmeter for stack gas

The ultrasonic flowmeter is a newly developed electronic intelligent flowmeter in recent years. It is widely used in various flow measurement situations and has a variety of forms. The ultrasonic flowmeter is based on the principle that the difference of propagation velocity of the ultrasonic wave between in the downstream and the upstream is related to the velocity of the medium; and combining the cross-sectional area of the measured pipeline, the instantaneous flowrate can be calculated. The ultrasonic flowmeter can be divided into liquid ultrasonic flowmeter and gas ultrasonic flowmeter according to the measured medium; insertion ultrasonic flowmeter and no-insertion ultrasonic flowmeter according to whether the transducer contacting with the measuring medium or not; single path ultrasonic flowmeter and multi-path ultrasonic flowmeter according to the number of paths. Because the stack gas flowrate measurement is mostly aimed at the built stack with the complex internal flow distribution, the insertion multi-path ultrasonic flowmeter has been applied to the measurement of stack gas flowrate and achieved good results in recent years.

4.2. The principle of flow measurement of multi-path ultrasonic flowmeter

The basic principle of flowrate measurement by ultrasonic flowmeter is as shown in Fig.4. A pair of transducers of the ultrasonic flowmeter are placed on both sides of the measured pipeline [5]. The propagation time of downstream ultrasonic wave is recorded as \( t_{d,i} \); and the propagation time of upstream ultrasonic wave is recorded as \( t_{u,i} \). Then the axial velocity of the acoustic path is as follows.

\[
\frac{u_i}{L_i} = \frac{1}{2 \cos \phi_i} \left( \frac{1}{t_{u,i}} - \frac{1}{t_{d,i}} \right) \tag{7}
\]

\( u_i \), the flow velocity of the path, m/s;

\( L_i \), acoustic path length, m;

\( \phi_i \), acoustic path angle, °.

![Fig.4. The basic principle of flowrate measurement by ultrasonic method](image)

Due to the existence of edge effect, the flow distribution in the pipeline is uneven, which results in inaccurate measurement result and undesirable measurement repeatability. The appearance of the
multi-path ultrasonic flowmeter and the maturity of the integral algorithm greatly improves the situation [6-7]. A number of cross acoustic paths are arranged parallely in different layers in the measured section as shown in Fig.5. The average flow velocity of the measured pipe section is calculated considering the weight of the acoustic paths, and then the instantaneous flowrate is calculated as formula (8).

$$q_v = R^2 \sum_{i=1}^{N} W_i \left( \frac{L_i}{\cos \phi_i} \right) f(t_{di}, t_{ui})$$  \hspace{1cm} (8)

$R$, cross section radius of the measured pipe, m;
$W_i$, weight, dimensionless;

Fig.5. A typical arrangement diagram of 2*4 acoustic path flowmeter with circular pipe

The weight and acoustic path height of a circular pipe can be determined by the Gauss-Jacobi or OWICS integral method; while the weight and acoustic path height of the rectangular pipe with different acoustic paths can be determined by the Gauss-Legendre or OWIRS integral method [8]. It is known from the formula (7) and (8) that the instantaneous flowrate of the measured section can be calculated as long as the flow velocity $u_i$, the pipe radius $R$, the acoustic path length $L_i$ and acoustic path angle $\phi_i$ of each path are measured.

4.3. Actual measurement

The actual measurand is still the stack shown in Fig.3. The transducers of the 2*3 paths flowmeter were installed between the top two layers of the stack platform (as shown in the picture). The weight $W_i$ and relative path height are chosen according to OWICS method. Namely, when the relative path height is 0 (middle layer), the weight $W_i$ is 0.768693. When the relative path height is 0.695561, the weight $W_i$ is 0.553707. The actual measured radius of the stack was 3.446m, and the installation plane were the center plane of the stack (across the axis) and the flanks 2.397m away from center plane. The length of the acoustic path on the flanks was 5.269m, and the angle of acoustic path was 70°; while the length of the middle layer was 7.334m, and the angle of acoustic path was 70°, too. The schematic diagram of the installation of 2*3 acoustic path ultrasonic flowmeter was shown in Fig.6.

The experiment of multi-path ultrasonic flowmeter was carried out at the same time with the experiment of S-type pitot tube. Therefore, the two methods for each flowrate point measurement are carried out under the same temperature and pressure conditions, the same fan frequency and the same water vapor content. The corresponding measurements of the flowrate after the correction of temperature and pressure were 80.5622*10^4 m^3/h, 171.0407*10^4 m^3/h and 401.168*10^4 m^3/h, respectively. In the middle frequency of the fan, the flow velocity of the first layer two paths were 4.47 m/s, 4.62 m/s, the flow velocity of the middle layer two paths was 15.98 m/s, 15.71 m/s and the flow velocity of the third layer two paths were 4.79 m/s and 4.83 m/s.
4.4. Uncertainty evaluation of flowrates measured by multi-path ultrasonic flowmeter

According to the principle of flowrate measurement by multi-path ultrasonic flowmeter, the measurement uncertainty is mainly caused by the uncertainty of radius, acoustic path length and acoustic path angle. The axis of the stack is obtained by the method of circumference equal division. During the process of transducers installation, the total station was used to determine the installation position; after the installation process, the total station was used to measure the acoustic path angle and the steel tape was used to measure the acoustic path length.

According to the evaluation method of measurement uncertainty, and based on formula (8), the relative standard uncertainty of flowrate measured by multi-path ultrasonic flowmeter can be calculated by the formula (9).

\[
\left( \frac{u(q_c)}{q_c} \right)^2 = \left( 2 \frac{u(R)}{R} \right)^2 + \left( \sum_{i=1}^{k} W_i u_{\mu_{\omega}} \frac{u(L_i)}{L_i} \right)^2 + \left( \sum_{i=1}^{k} W_i u_{\mu_{\phi}} \tan \phi u(\phi) \right)^2 + \left( \sum_{i=1}^{n} W_i u_{\mu_{\omega}} \right)^2
\]  

(9)

As it was used circumference equal division method to determine the position of the axis, which is a complex operation with many segments, so the uncertainty of the axis played an important role in the relative standard uncertainty of the path angle. According to the Calibration Certification of total station used in the measurement, the extended uncertainty of the angle measurement was 0.25"and the path angle was approximately 70°. So, the relative extended uncertainty of the path angle introduced by total station was 9.92*10^{-5}%. The relative extended uncertainty of mathematical model of circumference equal division method was 0.01%. Considering the normal distribution and the Type A uncertainty introduced by repeated measurements, the relative standard uncertainty of the path angle calculated by the second term of formula (9) was 0.31%. The same way, according to the calibration certification, the Type B relative standard uncertainty introduced by the steel tape in the path length...
and pipe radius was 0.001%. Combining with the Type A uncertainty introduced by repeated measurements, the relative standard uncertainty introduced by stack radius and path length were respectively 0.08% and 0.13%. So, the relative standard uncertainty of the stack gas flowrate obtained by multi-path ultrasonic flowmeter method was 0.35%.

5. Measurement results and comparison of two methods
According to the flow velocity of each point measured by the pitot tube, it can be seen that the closer the sampling point to the stack wall, the lower the stack gas velocity is, on the contrary, the closer the sampling point to the stack axis, the higher the stack gas velocity is. The result measured by the 2*3 ultrasonic flowmeter was also in agreement with the above situation. The average velocity of the 2 paths in the middle layer is the highest, while the velocity of the right layer and left layer two paths is much lower than that of the middle layer. Many reasons lead to this situation, mainly including 1) The distance between the right(left)layer and the stack wall is only 1.049m according to the OWICS method, and the boundary layer effect of closed tube fluid is obvious. 2) Under the condition of high temperature and high humidity, the unevenness of flow distribution is more serious than that of common condition. In terms of the value of flowrate measurement, the maximum deviation occurred at the minimum flowrate, and the relative deviation between the two methods was 2.25%. Then with the increase of flowrate, the deviation decreased gradually, and at the maximum flowrate, the flowrate deviation was only 0.49%. Moreover, according to the comparison result of longtime flowrate measurement by the two methods, the flowrate obtained by the multi-path ultrasonic flowmeter was relatively stable, and the repeatability of longtime measurement using this method was around 0.5%; while the figure was around 0.9% using S-type pitot tube. It is possible that the flow velocity measured by S-type pitot tube is easily influenced by the uncertain vortex in the stack. In addition, in terms of the relative standard uncertainty of flowrate, multi-path ultrasonic flowmeter method is better than S-type pitot tube method. It is mainly because the measurement of time difference is less likely to be influenced by the environment than the measurement of differential pressure.

6. Conclusion
The key points of filed measuring technology of flowrate for stationary emission source are the acquisition of structural parameters and the flow velocity measurement of the measured section. The structure parameters can be obtained by means of the total station and the three-dimensional laser scanner. Owing to the simple measurement principle and the low price, S-type pitot tube method is suitable for the situation with low requirements of accuracy and repeatability. While, for the newly-built stack, the multi-path ultrasonic method with high precision and good repeatability should be considered first, and the integral algorithm and the number of acoustic paths should be chosen carefully. For the newly-built stationary emission source with small cross-sectional area (diameter or equivalent diameter less than 1m), the pipeline ultrasonic flowmeter can be directly used in flowrate measurement. With this kind of flowmeter, the uncertainty of the path length and path angle is further reduced and the accuracy of the measurement will be highly improved.

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