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Acoustic method Temperature and velocity fields in the furnace Co-measurement method study

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Abstract. The combustion power field and velocity field of power station boiler chamber have a direct impact on the boiler operation economy and reliability, and the power field in the furnace must be measured collaboratively. However, the thermal conditions of the power field environment is harsh, the traditional method can not be effectively detected, non-contact acoustic wave method can be taken to measure, high precision, simple methods, real-time detection can be realized. Based on this, this paper briefly discusses the acoustic wave method furnace temperature field and velocity field measurement principle, the temperature field and velocity field model construction, acoustic wave trajectory to be analyzed, targeted reconstruction of the temperature field and velocity field, to carry out experimental testing, improve the measurement efficiency and quality, in order to provide reference for related workers.

Key words: acoustic method; temperature field; velocity field; synergistic measurements.

Furnace combustion medium velocity field, temperature field independent of each other, but linked, coupled to form a stable power field is to ensure the basis of operational safety and efficiency. Velocity field detection due to the complex characteristics of the vector field, considering the actual boiler operation, a variety of uncertainty factors can easily cause the furnace brushing the wall, tilt, etc., reducing combustion efficiency and stability. The temperature field and velocity field coupled with each other but not completely synergistic, only to understand the temperature field can not fully control the combustion situation in the furnace, we must understand the velocity field information, you can take the acoustic wave method to measure the temperature field and velocity field synergistically, which in turn provides a basis for the solution of the problems of the residual rotating, boiler coking and so on.

1. Principle of synergistic measurement of temperature and velocity fields in a furnace by acoustic method

1.1. Principle of temperature measurement

Acoustic wave as a mechanical wave, propagation in the fluid medium, while affected by the medium flow speed and temperature, according to the medium temperature and acoustic wave velocity as a function of the relationship between the linear superposition of the medium's own speed, to be able to measure the temperature and speed of the furnace[1]. Acoustic wave method of temperature measurement as a non-contact measurement technology, combined with known acoustic wave propagation distance, measuring the acoustic wave flight time to calculate the acoustic wave propagation velocity in the medium, and then measure the temperature of the medium. Without considering the air flow, combined with the acoustic wave propagation equations of motion, fluctuation equations, gas ideal equation of state, to obtain the temperature measurement equation is as follows:

$$c = \sqrt{\frac{\gamma R}{m} T} = Z\sqrt{T} \tag{1}$$

where.γ is the sonic constant pressure specific heat capacity in a gaseous medium: the value of the constant volume specific heat capacity, airγ is the yield 1.4;c is the speed of sound wave propagation in the medium;R is the molar gas constant;T is the absolute gas temperature;m is the gas molar volume.

$$Z = \sqrt{\frac{\gamma R}{m}} \tag{2}$$

Where, Z is a specific medium constant, the flue gas mixture Z value 19.08, air Z value 20.05. Therefore, the gas temperature can determine the speed of acoustic wave propagation, because most of the gas components rarely affect the speed of acoustic wave propagation, it can be regarded as temperature and the speed of acoustic wave propagation is a single-valued functional relationship[2] .

1.2. Principle of speed measurement

Acoustic wave propagation in the medium belongs to the longitudinal wave, the medium and the speed of sound flow linear superposition, considering the existence of flue gas flow velocity component in the direction of acoustic wave propagation, the use of acoustic wave method for propagation velocity measurement formula is as follows:

$$c' = w + c \tag{3}$$

wherec' is the actual sound wave propagation velocity;w Is the velocity component of the acoustic wave propagation direction. In the furnace flue, set up a double-layer acoustic wave sensor, can realize the interlayer send and receive acoustic signals, known at a certain moment temperature, a certain period of time to maintain stability to ensure that the measurement of the positive and negative directions at the same time, you can add or subtract the two formulas of inefficient acoustic wave propagation and the impact of flue gas flow to obtain a reconstruction of the distribution of the medium velocity and acoustic wave propagation velocity[3] . General medium flow velocity is less than 10m/s, then A, B opposite path on the sound wave propagation time and sound velocity, medium velocity formula is as follows:

$$\frac{t_{AB}+t_{BA}}{2} = \frac{L_{AB}}{c} \tag{4}$$

$$\frac{\triangle t}{2} = \frac{t_{AB}-t_{BA}}{2} = -\frac{L_{AB}ucos\theta}{c^2} \tag{5}$$

Among them.t_{AB} ,t_{BA} is the sound wave propagation time on the opposite paths A and B;$\triangle t$ is the time difference between the sound wave flying across the same path in the forward and reverse directions;c is the speed of sound;u is the medium speed;L_{AB} is the sound wave propagation path on the same path;θ is the angle between the cross-layer sound wave and the medium flow velocity.

In the velocity field and temperature field synergistic measurement, the acoustic wave sensor can be set up in a cross-section of the furnace, the acoustic wave signal is used to get the t-flying time, through the inversion technique, in order to obtain the acoustic wave sensor interlayer flow field. For the medium velocity in the furnace, due to the fixed acoustic wave receiver and transmitter positions, the knownL_{AB} propagation path, itsθ , the flow direction is also fixed, can be indirectly determined by the acoustic time difference between the round-trip flyover and speed, to determine the fluid flow[4] . And the same path in different directions propagation acoustic wave velocity sum, can be the media flow effects of inefficiency, only the static air sound velocity term, and the time difference between the fly-through can offset the media sound velocity, to obtain the media flow. Combined with the T and c function relationship, and u and c relationship, the (4), (5) formula can be regarded as the basis of the acoustic method of synergistic measurement of the temperature field and velocity field.

2. Modeling of temperature and velocity fields in the furnace

2.1. Modeling

Boiler internal medium velocity, temperature distribution is complex, take the acoustic method of measurement only consider the velocity field, the temperature field on the acoustic wave propagation effect, the measurement results are inaccurate, must consider the velocity field and temperature field coupling effect.

2.1.1. Temperature field model

According to the acoustic wave propagation characteristics, the construction of the temperature field model has crater symmetry, single-peak symmetry model, etc., taking into account the complexity of the actual combustion in the furnace, the temperature field gradient is larger, there is an obvious acoustic line bending situation [5]. In the model selection, the laboratory simulation furnace temperature conditions its gradient is small, for the low-temperature temperature field, combined with its distribution characteristics, to take the single-peak symmetric model, to determine the impact of acoustic wave propagation, the formula is as follows:

$$T(x,y) = 60 * e^{-\frac{1}{150^2}(x^2+y^2)} + 283.15 \text{ (Range of x and y values 125-125mm)} \quad (6)$$

Among other things, the$T(x,y)$ is the(x,y) temperature at the coordinates, with a maximum modeled temperature of 343.15K.

2.1.2. Velocity field model

According to the relationship between temperature and speed of sound, media composition and acoustic velocity relationship, in practice, due to the furnace containing fly ash particles and flue gas, the field distribution is uneven, radial and axial cross-section there is a concentration gradient, if it will be homogenized to deal with the error will be caused by[6] . Therefore, the medium velocity field inside the furnace is simplified to deal with the use of air-fluid medium instead of internal flue gas, and a wide single-peak velocity field model is taken, with the following formula:

$$u(x,y) = \frac{4}{1+\frac{1}{150^2}(x^2+y^2)} \text{ (Range of x and y values 125-125mm)} \quad (7)$$

Among other things, the$u(x,y)$ is the(x,y) velocity at the coordinates and the maximum modeled velocity is 4m/s.

2.1.3. Sound field modeling

In the acoustic measurement platform, a 100 kHz sinusoidal signal was selected to clarify the$f$ The relationship between the frequency of the sound wave and theλ The sound wave wavelength is related to c propagation speed as follows:

$$\lambda = \frac{c}{f} \quad (8)$$

25 °C room temperature conditions, sound waves in the air propagation speed of 340m / s, according to (1) formula to determine the room temperature temperature acoustic wave wavelength of 3.46mm, the temperature decreases, the acoustic wave velocity is also reduced, the same acoustic frequency, the acoustic wave wavelength is smaller. Sound field modeling, can take the sound line theory, when the wavelength is smaller than the model size, sound wave propagation can be seen as countless perpendicular to the isophase surface of the sound line, the sound line distance on behalf of the propagation path, the calculation is relatively simple. I consider acoustic measurements in the temperature field, velocity field requirements for a more convenient, intuitive method to determine its propagation characteristics to acoustic rays and acoustic paths, propagation time of the trajectory of the combination of the velocity field, the temperature field of the acoustic measurements of the impact. According to the ray acoustic equation can be known:

$$\begin{cases} \frac{\overrightarrow{dq}}{dt} = \frac{\partial \omega}{\partial \vec{k}} \\ \frac{d\vec{k}}{dt} = \frac{\partial \omega}{\partial \vec{q}} \\ \omega = c\left|\vec{k}\right| + \vec{k} + \vec{u} \end{cases} \quad (9)$$

where$\vec{k}$ is the wave vector, and$\left|\vec{k}\right|$ represents the angular wave number;$\vec{q}$ is the sound wave position vector; c is the propagating acoustic wave velocity; $\vec{u}$ is the ambient flow velocity; t is the propagation time;ω is the acoustic wave angular frequency.

2.2. Acoustic trajectories

Under the uniform temperature field, the acoustic wave propagation speed is the same, and the propagation array surface belongs to the regular circular arc, and the surface formed by the envelope of the ray front is centered on the acoustic source emission point to form the circular arc. Under the single-peak symmetric temperature field, coupling the acoustic wave propagation model with the temperature field model, using Comsol calculations, it is clear that there is a curved acoustic wave propagation front, and the curvature of the wave front increases in the part of larger temperature gradient. The velocity of the propagating acoustic wave is increasing under increasing temperature, and its propagation speed is faster.

Under the single-peak velocity field, coupled acoustic wave propagation model, the use of Comsol calculations, to determine the acoustic wave propagation without significant changes, assuming that the temperature field inside the furnace is uniformly distributed, the value of 288.15K, to determine the acoustic wave air propagation speed of 340m/s, the background medium flow velocity of the maximum of 4m/s, along the direction of the acoustic wave propagation of the linear superposition of the transformation of the acoustic wave propagation path of the vertical velocity component, to determine the speed of the velocity field of propagation of the acoustic wave Path, time has an impact, the longer the acoustic wave propagation time, the greater the impact, compared to the temperature field is slightly smaller.

3. Acoustic Reconstruction of Temperature and Velocity Field Measurements in the Furnace

3.1. Temperature field reconstruction

In the temperature field reconstruction, the least squares method is the most intuitive and simple reconstruction algorithm, which can find the unknown data and reduce the error between the actual data and the unknown data. Arrange the acoustic wave transceiver around the measured area to form an effective path m. The formula for the acoustic wave propagation time along any measurement path is as follows:

$$t = \int adS \quad (10)$$

where t is the propagation time; S is the propagation path length; a is the spatial characterization of the acoustic wave propagation path; and dS is the differential of the acoustic wave along the propagation path. The measured temperature field, take the inverse derivation of the positive problem, you can determine the center point temperature. The measured region assumes that the temperature position of each region, the reconstruction of the temperature field needs to be measured m path on the acoustic wave propagation time, inversion of the distribution of sound velocity in each region, the use of temperature and propagation velocity single-value function to reconstruct the temperature field. The formula is as follows:

$$t_j = \sum_{i=1}^{n} a_j S_{ig} \quad (11)$$

wheret_j is the sound wave propagation time along the jth path;a_j is the jth grid sound velocity inverse, corresponding to the grid temperature;S_{ig} is the length of the jth acoustic wave path across the i-grid path. A system of linear equations can be obtained by measuring 1 cycle as follows:

$$\begin{cases} S_{11}a_1 + S_{21}a_2 + \cdots + S_{m1}a_m = t_1 \\ S_{12}a_2 + S_{22}a_2 + \cdots + S_{m2}a_m = t_2 \\ \quad\quad\quad\quad \cdots\cdots \\ S_{1n}a_1 + S_{2n}a_2 + \cdots + S_{mn}a_m = t_n \end{cases} \tag{12}$$

The matrix form is Sa=t. a is to be measured, indicating that the temperature functions t and s in the furnace are m*n matrices, and this is used as a three-dimensional temperature field model to be solved using different algorithms.

t_j'If it is an actual propagation time measurement on path j, the differencet_j is the same as the difference betweent_j' formula is as follows:

$$\varepsilon_j = t_j' - t_j = t_j' - \sum_{i=1}^{n} a_j S_{ig} \tag{13}$$

Solving by the least squares method, we obtain the equation$0 = \frac{\partial}{\partial a_j}\sum_{j=1}^{n}(t_j' - \sum_{i=1}^{n} a_j S_{ig})^2$ that is$S \cdot S^T \cdot a = t \cdot S^T$.

Under different acoustic measurements, the areas to be measured are divided and arranged in different ways, and there are differences in the number of effective paths and areas, and if the S matrix is full rank, the system of equations belongs to the system of super-definite equations, and there is no exact solution. Combined with the properties of full-rank matrix, it is clear that S is a non-singular matrix, which can be solved by the least squares method, and the transformation is as follows:

$$a = (S \cdot S^T)^2 \cdot S^T \cdot t \tag{14}$$

All the elements in the matrix are acoustic wave propagation path flying time, can know the acoustic wave sensor arrangement mode, number, division method, etc., you can find the elements of the matrix, to obtain the corresponding temperature values are as follows:

$$T(x,y,z) = \frac{1}{a^2 Z^2} \tag{15}$$

Assuming a uniform temperature distribution in each region, the average temperature value can be known using equation (16) as the center point temperature, which in turn can be used to measure the temperature field distribution by interpolation.

3.2. Velocity field reconstruction

In accordance with the principle of acoustic method of speed measurement, the arrangement of acoustic transceivers, the formation of effective paths m, the propagation of acoustic wave time difference along any path is as follows:

$$\triangle t = \int -\frac{2u\cos\theta}{c^2} dS = \sum_{i-1}^{n} h_{ij} u_i \tag{16}$$

$$h_{ij} = S_{ij} - \frac{2u\cos\theta}{c^2} \tag{17}$$

where S is the propagating acoustic wave path length; u is the vertical average velocity of the acoustic wave propagation path; and dS is the acoustic wave differential along the propagation path. TakeS_{ij} is the j-path acoustic wave traversing i-region length;u_i is the spatial characterization of the average vertical velocity of the acoustic wave in region i.

$\triangle t_j'$In case of actual propagation path measurements on path j, the difference equation is as follows:

$$\varepsilon_j = \triangle t_j' - \triangle t_j = \triangle t_j' - \sum_{i-1}^{n} h_{ij} u_i \tag{18}$$

Using the least squares method, the interpolated sum of squares is obtained, Eq.$0 = \frac{\partial}{\partial u_i}\sum_{j=1}^{n}(\triangle t_j' - \sum_{i-1}^{n} h_{ij}u_i)^2$. To ensure that the equation has a solution, it is required that n ≤ m, the number of acoustic flight paths exceeds the number of spatial divisions, any two acoustic waves pass through the regional network with at least 1 difference, and the different 10,000 pass through at least 1 path, ensuring that each grid velocity in the system of equations occurs 1 time, and obtaining the matrix solution$u = (h^T \cdot h)^{-1} \cdot h^T \cdot \triangle t$. According to the matrix can be known as the fly-through time difference, to determine the number of sensors, set the mode, you can calculate the acoustic wave propagation in the grid vertical velocity value, reconstruction of the velocity field, and then the use of interpolation method to the overall measured area to expand, get the velocity field distribution .

3.3. Interpolation Methods

Similarly to the unitary function interpolation to construct the multivariate function interpolation, set the binary function in the plane lattice electrodynamic function values as follows:

$$z_{ij} = f(x_i, y_j) \tag{19}$$

Using Matlab software, the correlation function is taken to compute the difference and compute the binary data and ternary data interpolation as follows:

$$ZI = interp2(X, Y, Z, XI, YI, method) \tag{20}$$

$$VI = interp2(X, Y, Z, xi, yi, zi, method) \tag{21}$$

To formulate algorithms to compute the interpolation values, there are linear interpolation, nearest proximity interpolation, cubic interpolation, etc.

4. Simulation Analysis

Arrangement of sensors on a plane in the furnace, distribution of acoustic paths, determine the arrangement of 12 transceiver sensors, will be measured area coverage, set the furnace area of 10 * 10m, taking into account the calculation of time-consuming and accuracy, divided into small areas of 20 * 20. Determine the temperature field and velocity field by the least squares method, according to the number of sensors, select the number of basis functions 24, in order to reflect the flue gas velocity and temperature in the furnace, select the temperature field single-peak distribution of 1643 ℃, the velocity field of a single-vortex flow, the flow rate of 6.28m/s, and the temperature field of double-peak symmetric distribution of 1619 ℃, the velocity field of dual-vortex flow of 6.54m/s of the two working conditions.

In order to verify the temperature field and velocity field correction reconstruction model effect in the furnace, different distances to determine the sensor and the acoustic wave situation, after fixing the sensor, one end of the constant movement, the distance of 0.05 ~ 1.5m, to determine the changes in the situation, the measurement error is distributed on both sides of the accurate value, multiple measurements to take the average, to determine the relative error of 1.5%, to meet the requirements of the measurement.

5. Conclusion

In summary, the power station boiler system is complex and in a low-pressure and high-temperature state, coupled with the fact that coal combustion is characterized by harsh environment, huge equipment, turbulence, and transient changes, which leads to high difficulty in the measurement of temperature field and velocity field in the furnace, and the acoustic method can be adopted for non-contact measurements to improve the accuracy of the results. Therefore, in the acoustic measurement of temperature field and velocity field, it is necessary to clarify its mathematical principles, construct the corresponding coupling model, through the reconstruction algorithm, so as to meet the requirements of the acoustic method of measurement, to understand the velocity field and temperature field in the combustion, and to provide support for the improvement of the combustion efficiency in the furnace.

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