Numerical simulation of sintering bellows under multi-point leakage

Mingzhu Yu¹, Jin Cai², Xianghu Kong², Xiangwei Kong²*

¹Engineering and Automation General Ironmaking Plant Angang Steel Co., Ltd. Anshan, China
²School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China

xwkong@me.neu.edu.cn

Abstract. In order to study the influence of multi-point leakage on the flow field in the bellows and the quantitative evaluation method of air leakage based on temperature, the Fluent software was used to consider the fluid-solid coupling heat transfer in the bellows and the convection and radiation heat dissipation on the outer wall of the bellows. The multi-point leakage environment was set up, and the numerical simulation model of single-side sintered bellows-branch pipe section was established. The temperature distribution and flow field distribution of the fluid on the outer wall and inside the bellows are solved. Infrared thermal imaging was used to extract the temperature trend of the local leakage point of 5# bellows, and compared with the simulation results, it was found that the closer to the leakage point, the faster the temperature dropped, and the two had a strong correlation, which proved that it was feasible to use numerical simulation to study the air leakage of bellows. Through the analysis of different leakage forms, it is found that the influence range and intensity of single-point leakage and multi-point leakage on the field quantity are different. The research method lays a solid foundation for the in-depth study of temperature-based detection algorithm.

1. Introduction

Modern exhaust air sintering technology is the main method of the iron ore sintering, the air leakage of sintering system is a big problem restricting the sintering ore quality and output in the field of energy saving, the characteristics of air leakage of sintering is high air leakage rate, generally can reach 30%-60%, many parts and more air leakage, the reason and governance means each different, but lacks the effective on-line quantification evaluation method.

Jin Yonglong, He Zhijun [1-4], using small experiment combined with thermal equilibrium theory, the online calculation of air leakage rate by using calorimetry is proposed. Xia Jianfang, Feng Yi [5-6] using CFD method, Considering the air leakage in the bellows slide, the flow field and temperature field inside the sintering bellows are solved, and the influence of the air leakage on the layout of measuring points is discussed, Jiang Lijuan[7] used the sintering bed model to predict the temperature of grate gas and combined with calorimetry to form an expert system for diagnosing sintering air leakage, Zhang Anyu and Yi Chuijie[8-9] designed and adopted the on-board oxygen analyzer combined with the oxygen balance method to form an online air leakage rate detection system in the laboratory stage in chemical natural gas, urban construction gas pipeline and other fields. In a broader sense of the leakage problem, Fu Jianmin, Zhao Hongxiang et al [10-13] studied the pressure response and the influencing factors of leakage volume in gas and liquid phase pipeline leakage by combining...
CFD with experiment. A.Ebrahimi-Moghadam, M.Farzaneh-Gord et al.\[14-15\] used CFD analysis to study the leakage and diffusion of compressible gas in above-ground and buried pipelines, etc.

At present, most researchers only pay attention to the leakage problem in the fluid domain itself, and the working conditions are usually normal temperature. Since the temperature of the outer wall of the sintered bellows reflects the heat transfer characteristics and temperature characteristics under different leakage forms, it is necessary to extend the solution domain and coupling the heat transfer and heat dissipation of the wall under multi-point leakage. The research method will provide better help for the further research on the leakage detection algorithm.

2. Mathematical models
Take a 360 m$^3$ sintering machine in a factory as an example, as shown in figure 1, a total of 24 sets of bellows are arranged on both sides of the workshop. Slide floating seal is generally used between the sintering bellows and the trolley. Due to the large fluctuation of working temperature, there are large leakage gaps in the slide. Other parts of the material due to falling, wear, corrosion and other reasons, the formation of point leakage, the prototype of single-side bellow-branch section of sintering machine can be simulated through different boundaries. Because the bellows contain complex curved surfaces and fluid-solid coupling heat transfer, the commercial software Fluent is used to solve the problem.

2.1. Governing Equation
The fluid flow in the bellows under multi-point leakage follows the basic equations of fluid mechanics.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Momentum conservation equation:

$$\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \left[ \mu (\nabla \mathbf{v} + \nabla \mathbf{v}^T) - \frac{2}{3} \nabla \cdot \mathbf{v} \right] + \rho \mathbf{g}$$

Where $\rho$ represents the fluid density, $\mathbf{v}$ is the velocity vector of the fluid, $p$ is the pressure, is the dynamic viscosity, $\mathbf{g}$ is the gravity acceleration vector, and $t$ is the time.

Energy conservation equation:

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot \left[ \mathbf{v} (\rho E + P) \right] = \nabla \cdot \left( k_{eff} \nabla T - \sum_i h_i J_i \right)$$
where $E$ represents the specific heat capacity, $E = h - \rho / \rho + v^2 / 2$, $h$ is the enthalpy, $h = \sum Y_i h_i$, $Y_i$ is the mass fraction of species $i$, $J_i$ is the diffusion flux of species generated by concentration gradient, $k_{eff}$ is the effective thermal conductivity of fluid, and $T$ is the thermodynamic temperature.

The fluid motion in bellows is turbulent flow. To model the fluid motion rule accurately, the realizable $k - \varepsilon$ turbulence model was employed; it is relatively stable and computationally efficient. The calculation equation is as follows:

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot \left[ \rho \mu \left( \frac{\mu}{\sigma_k} \right) \nabla k \right] + G_k - \rho \varepsilon = 0$$  \hspace{1cm} (4)

and

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \varepsilon \nabla) = \nabla \cdot \left[ \rho \mu \left( \frac{\mu}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1k} \frac{\varepsilon}{k} G_k - C_{2k} \rho \frac{\varepsilon^2}{k}$$  \hspace{1cm} (5)

Where $k - \varepsilon$ represents the turbulence kinetic energy, $\varepsilon$ is the turbulent dissipation rate, $G_k$ is the turbulence kinetic energy generated by average velocity gradient. $C_{1k}$ and $C_{2k}$ are constants, $C_{1k} = 1.44, C_{2k} = 1.9$ in present model. $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.2$ are the Prandtl numbers for $k$ and $\varepsilon$, respectively.

Thermal conductivity differential equation of fluid-solid coupling system:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{pc} \nabla \cdot (\nabla T) + \frac{q_v}{\rho c}$$  \hspace{1cm} (6)

where $a = \frac{\lambda}{pc}$ represents the thermal diffusivity. $\lambda$ represents the thermal conductivity. $c$ specific heat capacity. $q_v$ is the heat generation per unit volume and time.

2.2. Computing domain and mesh

Figure 2 is the model and mesh diagram, (a) is the model, (b) and (c) is the mesh distribution. Considering the bar under the trolley as the bellows inlet, the inlet size is 2.68m*2.056m, the slide seal of the bellows was considered as rectangular slot equivalent air leakage point 1 with gap width of 2mm. Other air leakage points on the bellows formed due to wear and aging and other reasons were uniformly considered as circular equivalent air leakage point 2 with equivalent diameter of 50mm. The equivalent leakage point 3 was set on the branch pipe with equivalent diameter of 50mm and the outlet diameter of the bellows was 1.1m. Due to the heat transfer calculation involving the wall surface and the external workshop environment, the bellows wall is treated with solid wall. The thickness of the bellows wall is 0.01m, set as solid field, and the material is Steel. The hot flue gas inside the bellows is set as fluid field, and the material is Air, and the physical parameters are kept constant default. In order to facilitate coupled heat transfer analysis, the meshing is divided by the method of co-node between fluid and solid domains, since the three-dimensional model of the bellows and its branches contains complex surfaces and the pores of the leakage points are very small, the unstructured tetrahedral mesh is used to partition the bellows and their branches. The number of nodes is 638051 and the number of cells is 3479401.
2.3. Boundary and solution Settings

The measured flow rate of the large flue is $1.3 \times 10^6 \, m^3 / h$. Each bellows is converted according to the equal flow rate. The bellows adopt a speed inlet with an average flow rate of $v = 2.5 \, m / s$ and an inlet temperature fluctuation range of 323.15K to 1273.15K. The bellows adopt pressure outlet, the static pressure fluctuation range is -1000Pa to -16000Pa, and the temperature is uniformly set at 400K to reduce the influence of reflux. The air leakage outlet is set as the pressure outlet, the relative pressure is 0, and the temperature is normal temperature.

The empirical formula for calculating the convective heat transfer coefficient of the outer wall surface is as follows: $h = 5.3 + 3.6 w_f$. The wind speed is measured as 3.25m/s, and the heat transfer coefficient is calculated as $17W / (m \cdot k)$. The internal forced convection heat transfer coefficient does not need to be set separately. After the thermal coupling is set, FLUENT will automatically calculate the convection heat transfer between the inner wall fluid and the wall surface according to the temperature of the fluid and the inner wall surface, using the conservation of energy. The emissivity and absorptivity of the outer surface of the bellows are set at 0.8, and the external temperature is set at normal temperature. The Realizable k-ε equation was used to simulate the turbulence because of the jet impact caused by leakage.

3. Discussion of numerical simulation results

Due to the obvious local leakage of 5# bellows on site, the discussion is based on this bellows. The pressure difference was set as -2.7kPa, the inlet temperature was 348K, and the inlet velocity was 2.5m/s. Figure 3 is the temperature diagram of the outer wall and internal fluid cross section of the 5# bellows. (a) is the temperature distribution of the outer wall, (b) is the temperature of the vertical cross section, and (c-f) is the temperature of the fluid cross section from section 1 to section 5. It can be seen that the multi-point leakage causes the change of the internal flow field and the temperature of the outer wall surface, and at the same time, there is a fierce cold and heat exchange process near the leakage point.

Compared with the measured average temperature of the outer wall and the measured data of the internal flue gas in the sintering HMI, the simulation results are very close, with a difference of less than 2%. In order to further verify the correctness of the simulation, we used a thermal imaging instrument to collect the temperature of the outer wall of the bellows, and extracted the vertical and
horizontal temperature around the local leakage point center of 5# bellows, and compared it with the vertical and horizontal mark temperature of leakage point 2 and leakage point 3 in the simulation.

Figure 3. The temperature diagram of the outer wall and internal fluid cross section of the 5# bellows.

Figure 4 is the infrared thermal imaging diagram of the leakage point on the 5# bellows and the temperature diagram of the mark line of the local leakage point. The temperature at the center of the leakage point is high, while the temperature on the wall surface outward from the center of the leakage point is obviously low.

Figure 4. Infrared leakage point diagram and local temperature trend.
Figure 5 shows the temperature chart of mark line 2,3 of local leakage points obtained by numerical simulation. It is clear that trends are highly correlated. It should be noted that the temperature data at the center of the leakage point collected by infrared is difficult to confirm its location because it is irradiated to the interior of the bellows. However, in the numerical simulation, the outer wall data at the center of the leakage point is the default, so we use the average temperature of the section at the center of the leakage point to fill in the default temperature for convenience of comparison.

By comparing the temperature characteristics of the branch pipe, the outer wall and the temperature of the leakage point, it is proved that the numerical simulation results using the multi-point leakage method and considering the fluid-solid coupling heat transfer are reliable.

3.1. Field quantity distribution under different leakage forms

Figure 6-8 is the velocity vector diagram, fluid temperature diagram and outer wall temperature diagram of the drooping direct surface in different leakage forms. (a), (b), (c) and (d) respectively represent the state of no leakage, single circular hole leakage, single long slot leakage and double leakage. The cloud image clearly shows the flow state of air near the leak point and the influence of heat transfer on the surrounding area.
Figure 7. Temperature diagrams of the center section of the fluid with no leakage, single hole leakage, single slit leakage and double leakage.

Figure 8. Temperature diagrams of outer wall of bellows with no leakage, single circular hole leakage, single long slot leakage and double leakage.

Figure 6 to 8 (a) shows the fluid velocity vector graph, the fluid temperature cloud graph and the temperature graph of the outer wall of the bellows under the condition of no leakage, respectively. The changes are uniform and smooth. It can be seen from (b) that in the case of leakage point of single circular hole, the velocity changes sharply at the leakage point, and there is an obvious cooling effect of jet injection, which strengthens the thermal mixing process of the two gas streams. However, the influence scope is limited to the area around the leakage point and does not affect the outer wall surfaces on both sides. (c) is a long slit leakage. As can be seen from the velocity vector figure, whirlpool flow appears in the bellows, and the influence range is in the form of waterfall flow. As the gap is equal to the bellows, it has an obvious thermal influence on the temperature of the outer wall of the bellows. (d) refers to the coexistence of single-hole leakage and long-slit leakage. Compared with the single-hole leakage state, the intensity of jet flow and waterfall flow is somewhat weakened, and the jet flow line becomes slow, but the morphological trend remains the same. The influence of the combination of the two on the external wall temperature is shown in figure 8 (d).

Therefore, the position and form of the leakage state have a great influence on the heat transfer and heat dissipation effect, especially the jet impact caused by the leakage, which actually strengthens the heat transfer between the internal fluid and the wall.

4. Conclusions and Prospects
(1) In the case of multi-point leakage, the leakage causes the cooling effect of jet injection, which strengthens the heat transfer effect between the internal fluid and the bellows wall. (2) Through simulation and infrared thermal imaging experiments, we obtained the temperature characteristic curve of the local leakage point. It is found that the closer to the center of the leakage point, the faster the temperature of the bellows wall decreases, and the greater the temperature gradient is, which is a kind of common character around the leakage point. (3) The leakage form has a great influence on the
temperature field of the internal fluid and the bellows wall, and it is found that the influence range and intensity of the field quantity are different between the single-point leakage and the multi-point leakage.

Due to limited space, we did not discuss the comprehensive influence of multi-point leakage on heat transfer quantitatively, and did not cover the research on air leakage rate and infrared algorithm. However, the research method in this paper will become the basis for further research.

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