Flow field optimizing study of low temperature economizer in a coal-fired boiler

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Abstract. The complex structure of double inlet gas flue has a significant influence on gas flow field distribution in a 1000MW coal-fired boiler's low temperature economizer. In order to optimize gas flow field of the low temperature economizer with double inlet gas flues and reduce its failure rate, this paper presents a flow field simulation of the low temperature economizer based on the computational fluid dynamics (CFD). This numerical simulation was operated by using porous media model instead of the complex structure inside heat exchanger and the standard k-epsilon model. Velocity contours of a same vertical cross-section inside of inlet gas flue of the heat exchange zone in different numerical simulations were evaluated by the evaluation standard of RSM. The results of numerical simulation show that the main reasons for uneven distribution of flow field in economizer and its inlet gas flues are unequal diameter of flue elbow and straight flue, unreasonable setting of guide plate and diffusion flue elbow. After making structural optimization of the low temperature economizer such as equalizing elbow to the straight flue diameter and setting the guide plate reasonably, the flow field in the low temperature economizer and its flues are obviously improved.

1 Introduction

It will lead to energy loss and reduce the thermal efficiency of the boiler, if the exhaust gas temperature of boiler is too high. Taking a 410 t / h boiler as an example, the exhaust gas temperature of the boiler increases by 20 °C, the thermal efficiency of the boiler decreases by 1.5% ~ 2%, and the annual consumption of standard coal is about 4500 t [1-3]. As a result, the waste heat boiler can be used as the main heating equipment of the power plant, which can save the energy consumption of the flue gas and reduce the energy consumption of the condensation water[4]. A large number of finned tube bundles are set in the low temperature economizer, and the structure is extremely complex. If the air flow into the finned tube bundle area is uneven, the heat exchange efficiency will be reduced, and in serious cases, the tube bundle will accumulate ash, wear, vibration and other phenomena, which will increase the failure rate of the equipment[5-6]. The research shows that the unreasonable setting of guide plate in the flue of economizer will lead to uneven distribution of flue gas velocity, excessive local velocity, serious wear of local tube bundle of economizer, and eventually cause leakage of economizer[7]. The uneven distribution of flue gas velocity and high local velocity will cause the shedding frequency of Karman vortex street in the low temperature economizer to be close to the acoustic standing wave frequency of the flue, resulting in resonance and vibration of the low temperature economizer[8]. Therefore, in the design or transformation stage of low-temperature economizer, optimizing the flow field distribution inside the equipment and its flue can effectively reduce the failure rate of the equipment.

Zhu Dongsheng et al. [9] analysed the characteristics of fluid flow distribution in plate fin heat exchanger by using porous medium model. There is little research on the flow field simulation and optimization using porous media model, For the low temperature economizer of 1 000 MW coal-fired boiler. In this paper, the flow field distribution in the low temperature economizer and its flue of a 1 000 MW coal-fired boiler in a power plant is numerically simulated by using the CFD numerical simulation technology and using the porous medium model to replace the finned tube heat transfer zone of the economizer. The inlet flue of the low-temperature economizer of the boiler is a double flue structure. Due to the uneven distribution of air flow, vibration and wear phenomena occur. In this paper, the optimal structure design scheme is obtained by optimizing the structure of the low temperature economizer and simulating its internal flow field under different working conditions. This is of reference significance to the optimization design and transformation of the low temperature economizer of 1 000 MW coal-fired boilers.

2 Numerical simulation method

2.1 3D model

A low temperature economizer is set between the electrostatic precipitator and the desulfurization tower in the power plant for waste heat recovery, and the inlet flue

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gas temperature of the desulfurization tower is reduced to reduce the water vapor saturation in the flue gas, so as to reduce the consumption of desulfurization circulating water. After passing through two electrostatic precipitators, the boiler flue gas enters the low-temperature economizer through the double flue. Its geometric structure is shown in Figure 1.

A three-dimensional model with the size ratio of 1:1 to the low-temperature economizer is established by using the three-dimensional modeling software. The model is imported into the mesh generation software for mesh generation, and the local part is encrypted. Through the grid quality inspection, the grid quality is greater than 0.35, and the grid quality is high. In order to improve the calculation speed, the porous medium model is used to replace the finned tube heat transfer zone of the low-temperature economizer, and the strut structure inside the flue is ignored. The final model (only showing the grid of the low-temperature economizer) is shown in Figure 2.

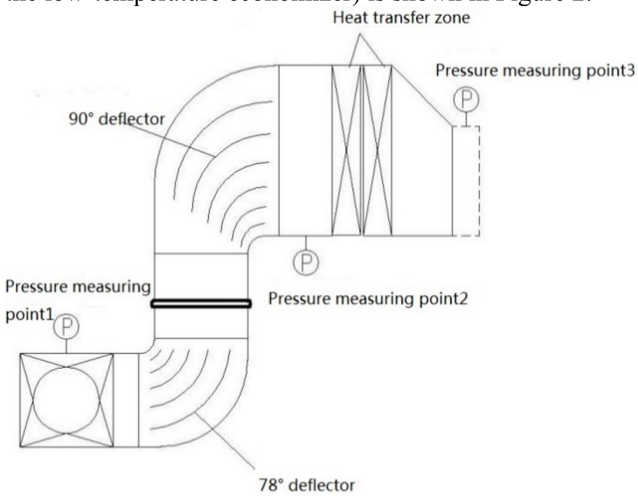

Fig 1 Elevation view of low-temperature economizer

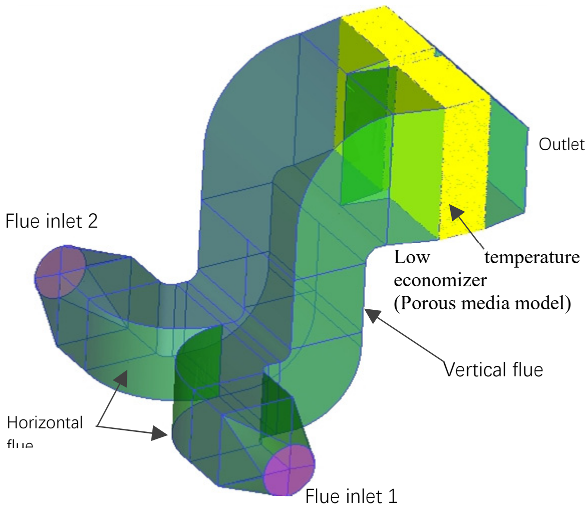

Fig. 2 Three-dimensional model of the economizer

2.2 Calculation model

The motion of fluid in nature conforms to three basic laws: the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy [10]. The mathematical description of these basic conservation laws is integral or differential control equations, which is the basis of calculating and analyzing the fluid flow and heat conduction in the low temperature economizer and its flue. The flow in the low-temperature economizer and its flue of a thermal power plant boiler is a three-dimensional turbulent problem. In this paper, the standard k-ε model is adopted, and the governing equations involved in the model are as follows.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho u)+div(\rho u\vec{v})=div(\mu grad u)-\frac{\partial p}{\partial x}+S_u \tag{2}$$

$$\frac{\partial}{\partial t}(\rho v)+div(\rho v\vec{v})=div(\mu grad v)-\frac{\partial p}{\partial y}+S_v \tag{3}$$

$$\frac{\partial}{\partial t}(\rho w)+div(\rho w\vec{v})=div(\mu grad w)-\frac{\partial p}{\partial z}+S_w \tag{4}$$

K equation of turbulent kinetic energy:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{5}$$

Governing equation of turbulent dissipation rate:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{\varepsilon 1}\frac{\varepsilon}{k}(G_k+C_3G_b)-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{6}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{7}$$

Where: ρ is fluid density, kg/m^3; t is time, s; p is hydrostatic pressure, Pa; u, v, w are velocity components in X, Y and Z coordinates respectively, m/s; $\vec{v}$ is fluid velocity vector; μ is hydrodynamic viscosity, Pa·s; S_u, S_v, S_w are the related source terms of other models in the corresponding coordinate direction; k is turbulent kinetic energy; ε is turbulent dissipation rate; G_k is the turbulent kinetic energy generated by laminar velocity gradient; G_b is the turbulent kinetic energy generated by buoyancy; Y_M is the wave generated by excessive diffusion in compressible turbulence; σ_k is the derivative of K equation, as 1.0; σ_ε is the turbulent Prandtl number of the ε equation, 1.3; x_i, x_j are coordinate positions; μ_t is turbulent velocity, m/s; S_k, S_ε is turbulent velocity; C_μ=0.09, $C_{\varepsilon 1}$=1.45, $C_{\varepsilon 2}$=1.92, C_3=1.

2.3 Porous media model

Because the structure of the finned tube bundle of the low temperature economizer is extremely complex, if the grid is divided according to the actual structure, the existing computer can not run. Porous medium model is a common assumption model in computational fluid dynamics, which can effectively simulate the flow and heat transfer characteristics in fin heat exchanger [11]. Therefore, the complex tube bundle area of low temperature economizer can be reasonably simplified as porous medium model [12]. The porous medium model adds a source term representing momentum consumption to the momentum equation, which is viscous loss term and inertial loss term respectively. By using the volume average method, the seepage velocity of fluid in porous media can be obtained.

The relationship between the seepage velocity and the velocity V of fluid flow in porous media is obtained by Dupuit Forchheimer equation.

$$u_s = \phi v \tag{8}$$

In this paper, the macro mass conservation equation in porous media can be expressed as

$$\frac{\partial(\phi\rho)}{\partial t} + \nabla(\rho\phi v) = 0 \tag{9}$$

$$S_i = \sum_{j=1}^{3} D_{ij}\mu v_j + \frac{1}{2}\sum_{j=1}^{3} C_{ij}\rho\left|v_j\right|v_i \tag{10}$$

Where:φ is the porosity of porous media,φ=0.856; S_i is the source term of momentum equation; v_i, v_j is the fluid velocity in different directions, m/s; D_{ij} is the viscous resistance coefficient, D_{ij}=0; C_{ij} is the inertial resistance coefficient, C_{ij}=(2×10^3,2×10^3,4).

2.4 Setting of physical property parameters

There are a lot of particles in boiler flue gas of thermal power plant. When the flue gas passes through the electrostatic precipitator, most of the particles are removed, so the flue gas entering the low temperature economizer can be simplified as single phase gas. According to the flue gas parameters of the boiler under BMCR condition, the main physical parameters of flue gas are set as shown in Table 1.

Table 1. Physical parameters of flue gas.

project	unit	parameters
Flue gas quantity	m^3/s	1191
Density of flue gas	Kg/m	0.883
Viscosity of flue gas	Kg/(m·s)	1.972×10^{-5}
Specific heat capacity	J/(kg·K)	1 006.43
Thermal conductivity	$W/(m^2·K)$	0.0242
Inlet flue gas temperature	°C	130.1

3 Flow field simulation and analysis

3.1 Numerical simulation results before structure optimization

According to the above settings, CFD software is used to simulate the flow field of the low temperature economizer and its flue under BMCR condition. The results show that the air flow in the vertical flue is inclined to the inside, which is caused by the unequal diameter of the elbow between the horizontal flue and the vertical flue, and the small turning angle of the deflector (only 76°). The phenomenon of local less flow appears at the top of the elbow of the vertical flue and the inlet flue of the low temperature economizer, and the gas flow velocity is 0~5 m/s. The air velocity at the bottom of the elbow of the vertical flue and the inlet flue of the low-temperature economizer is fast, and the vibration and wear are easy to occur at 11~17 m/s. The combined action of the above factors leads to the phenomenon of "too slow flow velocity at the top and too fast flow velocity at the bottom" in the air flow distribution of the entrance section of the low-temperature economizer. There is no air flow range at the top, while the air flow velocity at the local range of the middle and lower parts can reach more than 17 m / s, so that the smoke can not enter the low-temperature economizer evenly.

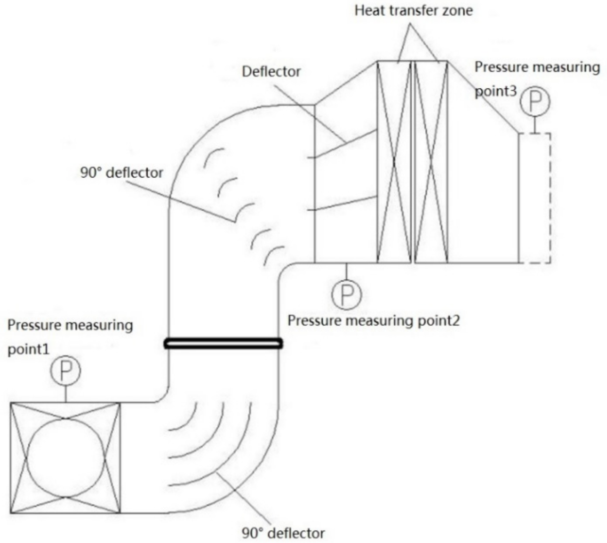

Fig 3 Flue structure after optimization

3.2 Structure optimization

According to Chinese technical specification, *Technical specification for design of flue gas, air and pulverized coal pipes in thermal power plants(DL 5121-2000T)*, the optimization method for selection of special-shaped flue , and the results of numerical simulation analysis before optimization, the structure of inlet flue of low-temperature economizer in the power plant is optimized. On the basis of the original structure, the lower elbow of the vertical flue is changed into an equal diameter elbow, and 3 deflectors with 90° turning angle are added, and the concentric circle of the deflector arc line is concentric with the concentric circle of the inner guard plate arc line; the upper elbow of the vertical flue is changed into an equal diameter elbow with the vertical flue, and 5 90° deflectors are set; the flue is connected with diffusion smoke after equal diameter turning 2 guide plates are set in the diffusion flue, and other structures are not changed, as shown in Figure 3.

3.3 Analysis of flow field distribution before and after structure optimization

The numerical simulation streamline of the low temperature economizer and its flue before and after the structure optimization, the middle section velocity nephogram of the left vertical flue, and the inlet section velocity nephogram of the heat transfer zone are shown in Figure 5~ Figure 9. It can be seen from Figure 4 and Figure 5 that, there was obvious phenomenon of too little local flow at the top of the inlet flue of low temperature economizer before the structure optimization, and the flow field distribution was uneven after the structure optimization, the phenomenon of too little local flow was significantly reduced. Before the flue structure is optimized, the flow direction of flue gas after passing through the guide plate at the bottom of the vertical flue deviates to the inside, and then passes through the expanded elbow flue to enter the low-temperature economizer. When the flue gas enters the low-temperature economizer, most of the flow is concentrated at the bottom of the elbow (Fig. 4 and Fig. 6). At the same time, because the upper elbow of the vertical flue is an expanding elbow, the internal pressure is reduced, resulting in too little air flow at the top, which leads to uneven air flow distribution at the inlet of the heat transfer zone, resulting in too little air flow at the upper part. The main reason for the uneven distribution of the flow field is that the structure of the upper and lower elbows of the vertical flue and the setting of the deflector are unreasonable.

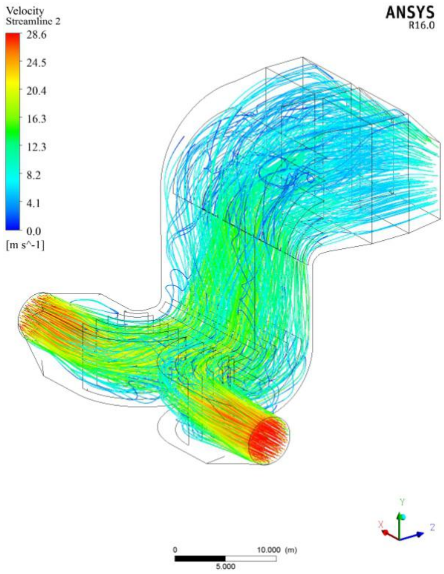

Fig 4 Streamline in the economizer before structure optimization

By optimizing the structure of the upper and lower elbows of the vertical flue, the upper and lower elbows are changed into elbows with the same diameter as the vertical flue, and the guide plate is set reasonably, so that the flow field uniformity in the vertical flue of the low-temperature economizer is significantly improved. Compared with before optimization, the phenomenon of gas flow deviation inside the vertical flue is obviously weakened, and the phenomenon of "too slow flow rate at the top and too fast flow rate at the bottom" of the elbow on the vertical flue is obviously weakened (Fig. 5 and Fig. 7). The upper elbow of the vertical flue is connected with the diffusion flue, and the local structure optimization makes the air flow uniformity at the inlet of the heat exchange area of the low temperature economizer significantly improved, and the flue gas velocity is 5~9 m/s (Fig. 8 and Fig. 9).

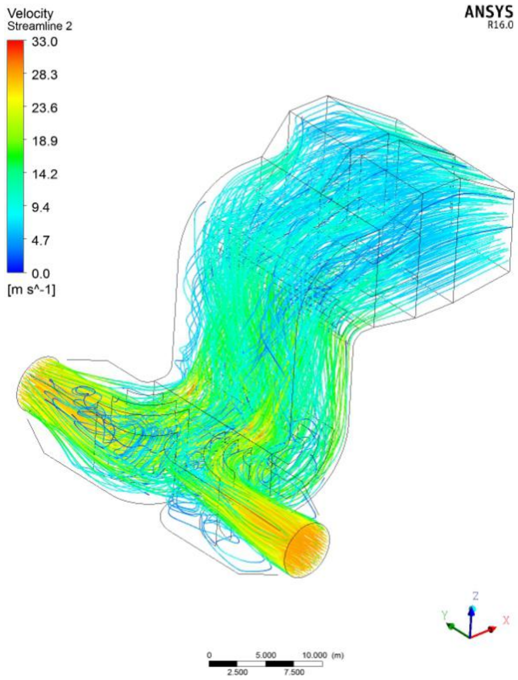

Fig 5 Streamline in the economizer after structure optimization

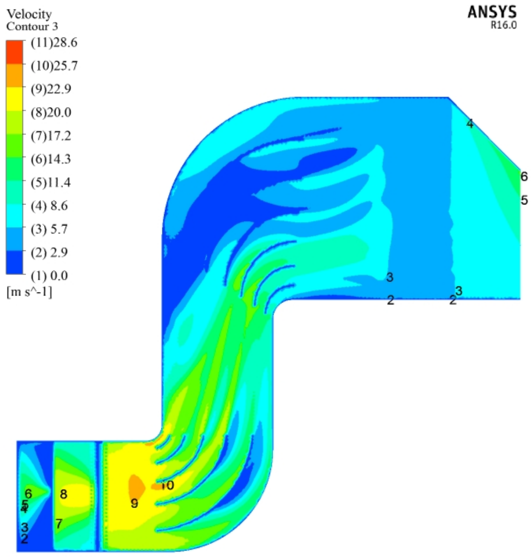

Fig.6 Velocity contour at lengthwise section of left vertical flue before structure optimization

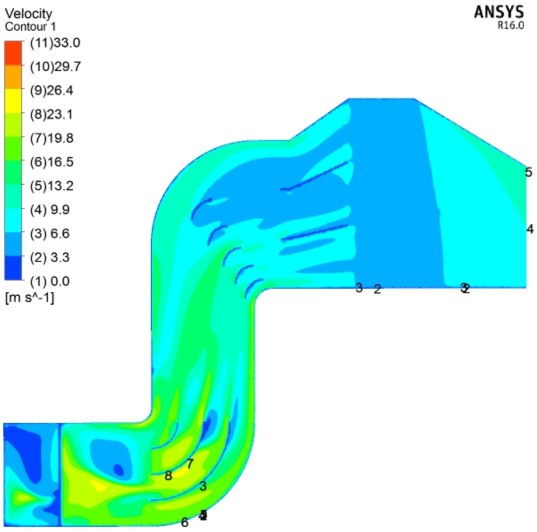

Fig. 7 Velocity contour at lengthwise section of left vertical flue after structure optimization

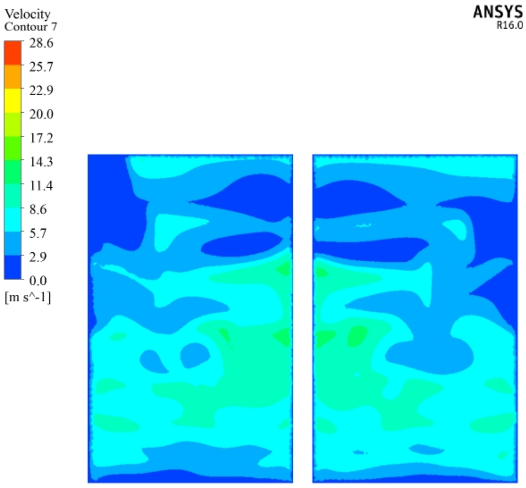

Fig. 8 Velocity contour at lengthwise section of inlet flue before and after structure optimization

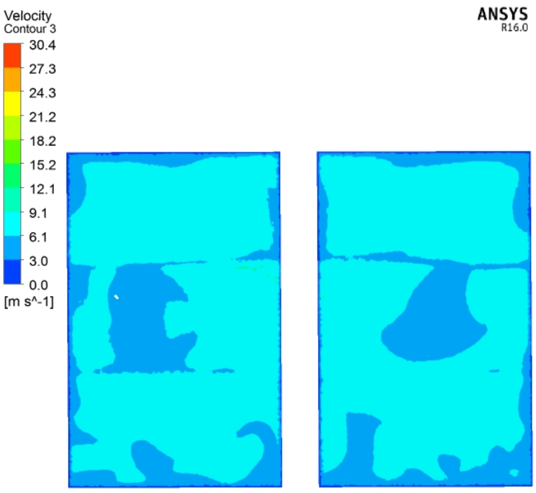

Fig. 9 Velocity contour at lengthwise section of inlet flue before and after structure optimization

3.4 Evaluation of flow field distribution

According to the evaluation method of airflow uniformity (RSM method) (equation 11)[13], the velocity uniformity of the inlet section of the finned tube heat transfer zone before and after the optimization of the low temperature economizer was evaluated under the conditions of different boiler loads corresponding to the flue inlet velocity of 3.7, 6.1, 8.5, 9.7 and 12.2 m/s. After several times of numerical simulation, the results show that before the structure optimization, when the flue gas velocity reaches 5.3m/s, the airflow distribution at the inlet section of the heat exchange zone of the low temperature economizer is unqualified, and the uniformity becomes worse with the increase of boiler load. After structure optimization, with the increase of flue gas flow rate, the uniformity of gas flow distribution at the inlet section of heat exchange zone of low-temperature economizer becomes worse, but all remain in the excellent range (Fig. 9). After the structure optimization, the uniformity of the air flow distribution at the entrance section of the heat exchange zone is significantly improved.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{v_i - \overline{v}}{\overline{v}}\right)^2} \times 100\% \qquad (11)$$

Where, σ is the uniformity coefficient, the relative root mean square value of the cross-section airflow velocity, % ; $\overline{v}$ is the average value of the cross-section airflow velocity, m/s; y_1 is the airflow velocity value of the measuring point in the cross-section, m/s, q is the measuring point on the cross-section. σ≤10%, express the air distribution is excellent ; 10% < σ≤15%, the air distribution is good ; 15% < σ≤25%, the air distribution is qualified.

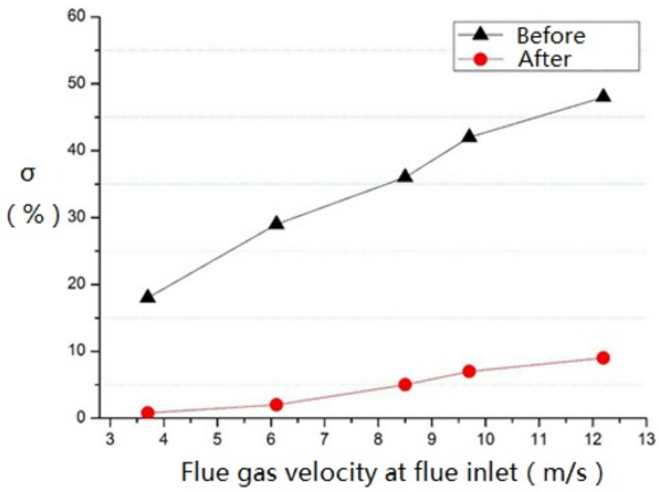

Fig 10 Streamline in the economizer before structure optimization

4 Conclusion

1) In this paper, the standard k-ε model is used to simulate the low temperature economizer and its flue of a 1 000

MW coal-fired unit by using porous media instead of complex tube bundle heat transfer zone. It is considered that the unequal diameter of the lower elbow and the flue, the diffusion elbow of the upper elbow and the unreasonable setting of the deflector are the main reasons for the uneven distribution of the flow field.

2) The upper and lower bends of the vertical flue of the low temperature economizer in this paper are changed to the bends with the same diameter as the vertical flue, and the guide plates are set reasonably, so as to solve the problem of uneven distribution of airflow in the flue. The phenomenon of airflow deviation in the flue of the low temperature economizer is obviously weakened, which makes the airflow enter the heat transfer area of the low temperature economizer more evenly.

3) Numerical simulation is used to analyze the cause of uneven flow field in low temperature economizer with double inlet flue. It is considered that the equal diameter of elbow and straight flue at the corner of flue is beneficial to improve the uniformity of gas distribution in flue. When the flue needs to be connected to the diffusion flue after turning, the flue should be connected to the diffusion flue after equal diameter turning, which is conducive to improving the uniformity of gas distribution in the flue.

References

1. N. Xianyong, Petrochemical Industry Technology, **25**, 19-20. (2018).
2. X. Kai, L. Qiang, Clean Coal Technology, **18**, 98-101. (2012).
3. Y. Fuxin, T. Houzhang, Z. Junjie, Clean Coal Technology, **24**, 124-128. (2017).
4. X. Gang, X. Cheng, Y. Yongping, Proceedings of the CSEE, **33**, 1-8. (2013).
5. Y. Yongzhi, Guangdong Electric Power, **28**,33-35. (2015).
6. L. Wei, G. Bin, W. Zongyong, Boiler Manufacturing, **9**, 7-9. (2010).
7. W. Jue, D. Yue, C. Chao, Mechanical Engineer, **6**, 155-158. (2018).
8. L. Jian, Q. Songbo, Power Equipment, **31**, 438-441.
9. Z. Dongsheng, M. Wei, L. Shaojian, Fluid Machinery, **40**, 63-67. (2012).
10. Y. Yue-Tzu, H. Ming-Lu, International Journal of Heat and Mass Transfer, **52**, 2956-2965. (2009).
11. L. Yukun, L. Quan, M. Qiang, Journal of North China Electric Power University, **04**, 38-43. (2008).
12. Z. Yongkai, J. Pengbo. Power System Engineering, **24**, 68-69. (2008).
13. L. Tan, J. Shiping, Thermal Power Generation,**42**, 60-63. (2013).