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Article

The Elaboration of Flow Resistance Model for a Bag Filter Serving a 200 MW Power Plant

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Abstract: On the basis of a macro flow resistance method and the Darcy Theory, a mathematical model is elaborated to characterize the flow resistance of a bag filter serving a coal-fired power plant. The development of the theoretical model is supported through acquisition of relevant data obtained by scanning the micro structure of the bag filter by means of an electron microscope. The influence of the running time and boiler load on the flow resistance and the impact of the flow resistance on the efficiency of the induced draft fan are analyzed by comparing the results of on-site operation tests. We show that the initial operation time and the table operation time are linearly related to the flow resistance of the bag filter; with the increase of boiler load, the flow resistance of the bag filter rises approximately as a quadratic function; with the rise of resistance, the power consumption of the induced draft fan increases while the efficiency of the induced draft fan decreases.

Keywords: Macro flow resistance method; Darcy Theory; bag filter; running time; boiler load

1 Introduction

Pollutants from the thermal power industry account for a considerable portion of air pollution emissions [1]. During combustion, pulverised coal inevitably produces dust and toxic and harmful gases [2–4]. Bag filters, also known as bag dust collectors, are a widely used dry dust removal device. Dust-containing airflow passes through filter bags in one direction, with dust particles blocked on one side and clean gas flowing through the filter bag, which filters flue gas. As a major equipment for controlling dust emissions from thermal power plants, these collectors are widely used due to their remarkable flue gas treatment capacity, dust removal effectiveness and strong applicability. Moreover, the application of electrostatic precipitators is restricted to some extent due to high resistance, fine grey matter of fly ash in thermal power plants and large dust content in the entrance of dust removers. To compensate for these limitations, the bag filter gains more widespread application all over the world [5].

For bag filter selections and designs, Guo [6] proposed suitable occasions for different types of bag filters and thus created conditions for the further promotion of dust removal equipment. Later, Zhao et al. [7] cooperated with professional institutions to design a large-scale pulse bag filter, which improved the efficiency of dust removal to a certain extent and provided a reference for the application of bag filters in large factories.

Afterwards, many experts also studied the internal flow fields of bag filters. Morcos [8] studied the relationship between dust particle size and dust removal efficiency by using test equipment and obtained some test data with reference significance. Koch et al. [9] conducted a study on dust particle size and dust removal effect and found that the pressure loss of dust with a uniform particle size is greater than that with a nonuniform one. Boudhan et al. [10] studied bag filters that were matched with garbage incinerators and concluded that the higher the flue gas humidity, the lower the filtration efficiency. The analysis of Leith et al. [11] revealed that the proportion of dust removal by blowing the pulse of bag filters is directly proportional to the reverse pressure drop during blowing; this finding provides a reference for practical applications.

For the structural improvements of the bag filter, Jin et al. [12] added active carbon in the bag filter to absorb dioxins in the flue gas effectively. Zhu et al. [13] designed a new structure for electrostatic bag filters, thereby improving the efficiency of dust removal to a certain extent. Hao et al. [14] added an orifice plate inside bag filters, which allow flue gas to flow uniformly, subsequently decreasing flow resistance.

Although substantial research has been conducted on the external structures of the bag filter and the internal materials of the filter bag, research on the overall resistance model is rare, and the existing models are often based on the resistance loss caused by the filter bag and the dust layer. Thus, the influence of the shell of the bag filter and the flue on the overall flow resistance is not considered, and the calculation model of the flow resistance caused by the increase in resistance still needs further optimisation. Therefore, on the basis of the macroscopic pressure loss method and Darcy theory, an overall flow resistance model of bag filters is established in consideration of the overall structure and the internal filter bag. The proposed model is verified through experiments and electron microscopy. The effects of flue gas flow rate and boiler load on the flow resistance of bag filters are studied from macroscopic and microscopic perspectives.

2 Establishment of a Flow Resistance Model for Bag Filters

The structure, filter bag resistance and dust resistance of bag filters are the major factors that influence the increase in flow resistance. Whilst the flow resistance caused by structural resistance mainly includes path and local resistance. Fig. 1 shows a structure diagram of a bag filter. Given that bag filters have a filter gas speed, the flue gas is generally in the laminar flow area, and the inlet and outlet distances are relatively close; thus, the resistance along the path can be neglected, and the total flow resistance of the bag filter can be expressed as

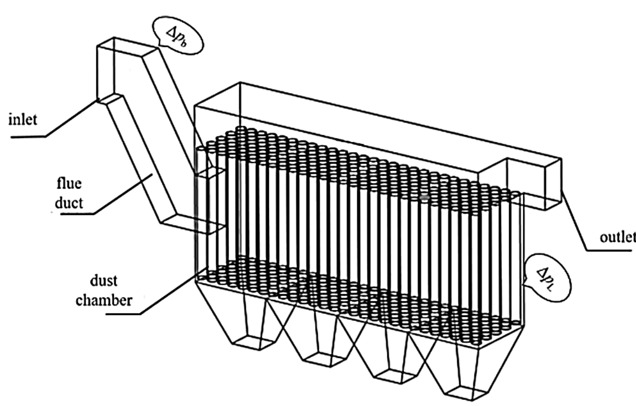

Figure 1: Structure diagram of a bag filter

$$\Delta p = \Delta p_{\mathrm{b}} + \Delta p_{\mathrm{L}} \tag{1}$$

where Δp_{b} is the local flow resistance, which mainly includes the resistance caused by the inlet and outlet flue and the large angle turning inside the bag filter, Pa; Δp_{L} is the sum of filter bag and dust flow resistance and caused by the flue gas around the filter bag and the dust layer attached on the outside, Pa.

Local flow resistance is mainly caused by the large angle turning of the inlet and outlet flue. For the large angle turning of the interior, the local loss coefficient can be approximately expressed as [15–17]

$$\zeta = 0.946\sin^2\left(\frac{\theta}{2}\right) + 2.05\sin^4\left(\frac{\theta}{2}\right) \tag{2}$$

Therefore, the flow resistance caused by internal large angle turns is

$$\Delta p_b = \frac{\rho v^2 \zeta}{2} \tag{3}$$

That is, Δp_{b} can be expressed as

$$\Delta p_{\mathrm{b}} = \rho {v_1}^2 n \sum_{\mathrm{i}=1}^{\mathrm{m}} \left[0.473 + 1.025\sin^2\left(\frac{\theta_{\mathrm{i}}}{2}\right)\right]\sin^2\left(\frac{\theta_{\mathrm{i}}}{2}\right) \tag{4}$$

where θ_{i} is the angle of the flue gas flowing through the flue and the inside of the precipitator,°; ρ is the inlet flue gas concentration, kg/m^3; n is the number of filter bags; v_1 is the velocity of flue gas at the entrance, m/s; m is the number of corners inside the bag filter.

The macroscopic flow resistance analysis method is used to consider the entire filter layer, without analysing the resistance of a single fibre or particle. Moreover, the test conditions are generally under laminar flow. Darcy theory [18,19] shows that the resistance of the clean fibre layer and the filtration of the layer thickness is proportional to the square of the incoming flow velocity. The relationship between the incoming velocity and the inlet velocity can be derived from Eq. (5); thus, the dynamic variation of total flow resistance during the filtration process is

$$A_1 v_1 = A_2 v_2, \tag{5}$$

$$\Delta p_{\mathrm{L}} = C_1 n H \frac{A_1}{A_2} v_1 + C_2 c_0 n \frac{A_1^2}{A_2^2} v_1^2 t, \tag{6}$$

where A_1 is the inlet sectional area of the bag filter, m^2; A_2 is the filtration area, m^2; v_2 is the filtration speed of the bag filter, m/s; C_1 and C_2 are resistance coefficients, which are generally measured by tests; H is the thickness of the fibre layer, m; C_0 is the dust concentration of inlet flue gas, g/m^3; t is the filtering time, s.

$$\Delta p = C_1 n H \frac{A_1}{A_2} v_1 + C_2 c_0 n \frac{A_1^2}{A_2^2} v_1^2 t + \rho v_1^2 n \sum_{\mathrm{i}=1}^{m} \left[0.473 + 1.025\sin^2\left(\frac{\theta_{\mathrm{i}}}{2}\right)\right]\sin^2\left(\frac{\theta_{\mathrm{i}}}{2}\right) \tag{7}$$

According to Formula (7), when the flue gas flow rate is constant (i.e., the filtering gas speed of the bag filter is stable, ignoring the influence of other factors), the flow resistance of the bag filter is initially positively related to time; under an unsteady state condition, the flow resistance of the bag filter is positively related to the flue gas flow rate in a second time. Therefore, $\Delta p = f(v^2 t)$.

3 Tests Affecting the Flow Resistance of Bag Filters

To verify the correctness of Formula (7), the bag filter of a 200 MW coal-fired unit of a power plant is selected as the research object. The external structure of the bag filter is shown in Fig. 2. The filter bags used are all updated during the unit's overhaul. The test uses the control variable method to record relevant data.

Figure 2: External structure of a cloth bag filter

3.1 Design Parameters of the Bag Filter

Tab. 1 shows the design's coal quality and the actual coal quality used in the power plant. The actual coal moisture and N and S content are high. To reduce the corrosion of the acid filter bag in the bag filter, the newly replaced filter bag of the power plant is made of needle-punched felt covered with a PTFE filter bag. The size of the filter bag is Ø130 × 8065.

To ensure the filter area of the bag filter, the design uses fork row arrangement, and the filtering wind speed is 0.80 m/min; the remaining operating parameters are shown in Tab. 2.

Table 1: Coal quality analysis

Project name	Unit name	Design of coal type	Actual coal type 1	Actual coal type 2
Water content	%	28.15	31	31.8
Moisture of air-drying base	%	12	12	5.87
Receiving base ash	%	21.49	25.86	12.24
Dry volatiles without ash base	%	42.38	49.9	48.71
Received base nitrogen content	%	0.62	0.64	0.81
Received base oxygen content	%	9.6	8.43	10.51
Total sulphur content	%	0.46	0.51	0.23
Received base-low calorific value	MJ/kg	13.82	11.32	14.91

Table 2: Coal quality analysis

Number of filterbags (n)	Inlet dust concentration (g/m^3)	Number of bends at the entrance (N)	Entrance turning angle	Number of bends at the exit (N)	Filter bag thickness (m)
1997	35	2	120°	0	0.003

3.2 Effect of Operation Time on Flow Resistance

Starting the unit takes approximately 4 × 10^5 s (approximately 1.1 × 10^2 h), with other factors kept unchanged. When only the influence of time on the flow resistance of the bag filter is considered, the flow resistance at different times and under the same load in this value range can be recorded, and data points A to B can be obtained in Fig. 2. Up until 4.5 × 10^5 s (1.25 × 10^2 h) when the unit continues to run smoothly under full load, relevant data can be recorded to obtain data points C to D in Fig. 3.

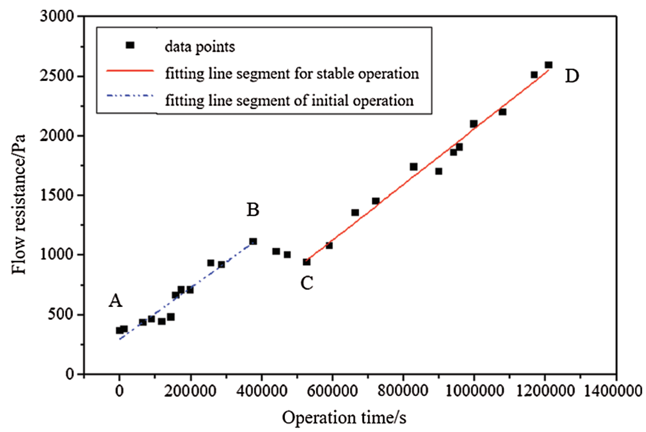

Figure 3: Relationship between flow resistance and operation time of the bag filter

Fig. 3 shows that when the bag filter is used as cleaning filter material, the flow resistance rises rapidly. When the operation reaches 4 × 10^5 s (approximately 1.1 × 10^2 h), the flow resistance suddenly turns downward, the operation continues for 1.5 × 10^5 s (approximately 4.2 × 10 h) and the flow resistance rises again rapidly. This phenomenon occurs because the cleaning filter material has high porosity. When the filter is run for a period, the gap between the filter material is gradually blocked, forming a dust layer on the outer side; this layer increases the overall resistance. After a long period of operation, the dust layer cannot adsorb more particles due to the limited force between the dust particles; thus, its thickness remains unchanged.

The two line segments are fitted as $p_1 = f(t)$ and $p_2 = f(t)$, respectively, and R^2 is 0.92 and 0.98. R^2 denotes goodness of fit, which is a measure of the exact row of the fitting formula. The closer R^2 is to 1, the better the fitting degree, and vice versa. Given that 0.936 and 0.978 are close to 1, the correctness of Formula (7) is proven.

To verify the presence of a dust layer, the filter bag is observed after it has run for 1.2 × 10^6 s (3.3 × 10^2 h) (Fig. 4). The attached dust layer is clearly visible in the windward side of the filter bag.

To verify the blocking phenomenon of the filter bag, the windward side of the filter bag is observed using an electron microscope. The result is shown in Fig. 5, which illustrates that more dust particles are present between the fibre. The presence of these particles considerably reduces the permeability of the filter bag. This result is consistent with that of the rapid increase in flow resistance in the previous stage of Fig. 3.

Therefore, after the bag filter stabilises, flow resistance can be initially calculated on the basis of the running time and the flow resistance model. If the actual measured flow resistance deviation is large, then it should be maintained and repaired in time.

Figure 4: Dust layer on the windward side of the filter bag

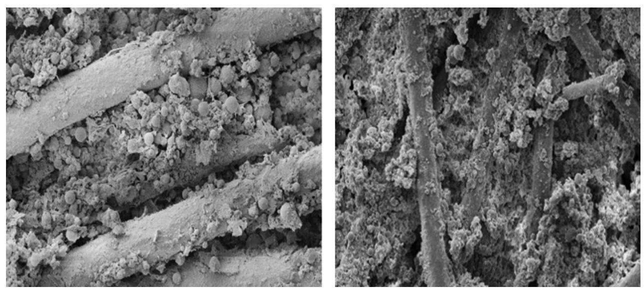

Figure 5: Electron microscopy of the windward surface of the filter bag

3.3 Effect of Boiler Load on Flow Resistance

The change of boiler load mainly affects coal and oxygen consumption, subsequently leading to a change in the amount of flue gas; these two variables are positively correlated [20,21]. The structure of the exhaust pipe and the bag filter is certain, and other factors, such as air leakage, are ignored; thus, the change of the boiler load results in the change of the flow rate of the flue gas. Therefore, the relationship between boiler load and flow resistance can be analysed to verify the influence of flow rate on flow resistance.

On the basis of the control variable method, a TH880W flue gas sampling instrument is used to test in the same time interval (5×10^5 s, i.e., 1.4×10^2 h). The test is divided into three parts: the boiler start-up, boiler initial stable operation and boiler long-term stable operation processes. The relationship between the change of boiler load (flow rate) and the flow resistance of the bag filter under these three conditions is statistically analysed. With other influencing factors ignored, Fig. 6 is obtained.

The first set of data in Fig. 6 shows that as the boiler load initially increases, the flow rate increases accordingly, the initial layer of dust outside the new filter bag begins to form and the overall flow resistance of the bag filter increases continuously.

The second set of data indicates that after the initial layer of dust is completely formed, the flow rate increases with the increase in boiler load in the same time interval. Moreover, the overall flow resistance of the bag filter rises rapidly in a flat manner.

The third group of data shows occurrences after the boiler has run for a long time; as the boiler load increases, the flow rate increases, and the overall flow resistance and flow rate increase in a square relationship. Three groups of formulae are obtained via fitting: $p_1 = 5 \times 10^{-4}v^2 + 1.77v$, $p_2 = 1.4 \times 10^{-3}v^2 + 0.56v$ and $p_3 = 3.6 \times 10^{-2}v^2 + 14.47v$. R^2 is 0.979, 0.953 and 0.912, respectively, indicating that the fitting results are accurate. Three groups of experimental data show that the flow resistance and load

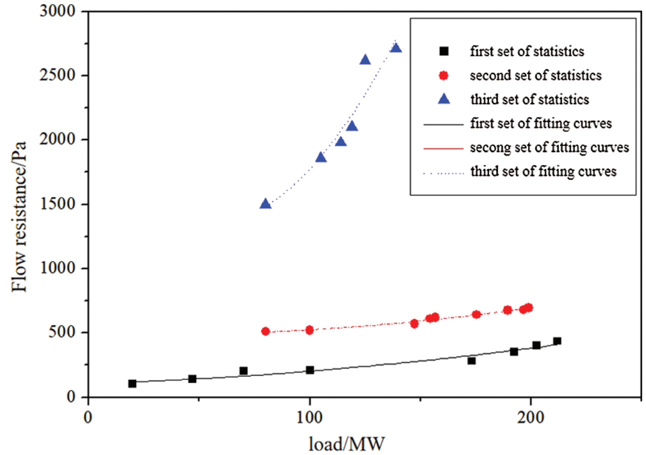

Figure 6: Relationship between the boiler load and the flow resistance of the bag filter

(flow rate) have a square relationship when the boiler runs steadily for a long time. This result further verifies the correctness of Formula (7).

The flow resistance model can be used for comparison with the actual measured values during operation. If the two deviations are large, then the internal components and design values of the bag filter are proven to be greatly deviated, thus requiring timely maintenance.

3.4 Effect of Flow Resistance on the Efficiency of the Induced Draft Fan

Induced draft fan is driven by a motor through a hydraulic coupler. Given that the voltage is constant, the efficiency of induced draft fan can be obtained by analysing the current required by the motor. When the flow resistance of the bag filter increases, the current of the induced draft fan is recorded; the relationship between flow resistance and energy consumption is shown in Fig. 7.

Fig. 7 shows that with the increase in flow resistance, the current required by the induced draft fan gradually increases. This relationship indicates that the energy consumption of the dust removal equipment and the operation cost of the power plant increase, thus reducing the total efficiency.

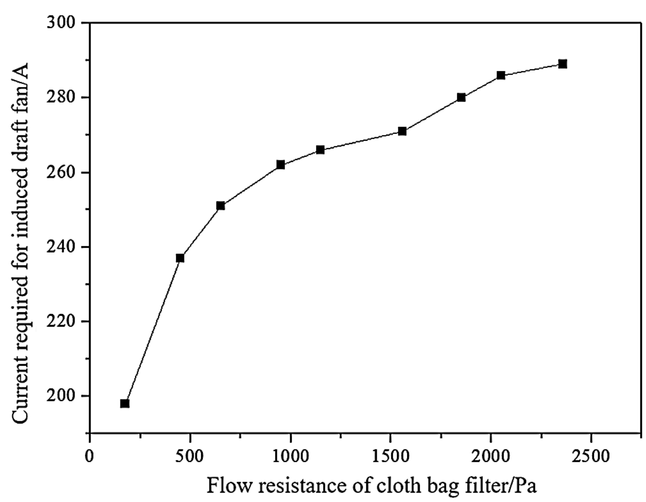

Figure 7: Relationship between the flow resistance of the bag filter and the current required by the induced draft fan

4 Conclusion

A flow resistance model of bag filters was established using the macroscopic flow resistance method and Darcy theory. The flow resistance test was used to verify the model. The following conclusions were obtained:

1. An overall flow resistance model of the bag filter is established: $\Delta p = \Delta p_b + \Delta p_L$.
2. Theory and experiment show that flow resistance is proportional to the square of speed and the first power of running time. Furthermore, the phenomenon of dust blocking filter bag and the flow resistance model are verified using an electron microscope.
3. An increase in flow resistance increases the energy consumption of the induced draft fan and reduces the overall efficiency of the unit. This result provides a basis for comparison between actual safety and economic operation.

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