Mathematical Modeling of Filtration Efficiency of Granular Bed Filter Based on Semi-Coke as Filter Medium

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Keywords: Granular Bed Filter, Semi-Coke, Filtration Efficiency, Mathematical Model, Characteristic Parameter.

Abstract: In order to more accurately describe the change of the filtration efficiency of the granular bed filter using semi-coke as the filter medium during the whole filtering process, the effects of the apparent gas velocity, filter material thickness and filter material particle size on the filtration efficiency of the granular bed filter were investigated on a cold state experimental device, taking into account the changes in bed voidage, dust deposition on the filter material surface, and secondary entrainment, The mathematical model of unsteady filtration efficiency is derived theoretically, and the correction coefficient expression of the filtration coefficient in the particle bed filtration model is introduced as F(σ)=(1+bσ)n1(1-aσ)n2, fitting the experimental results under different operating conditions with Matlab programming software, and obtaining the values of characteristic parameters a and b. Within the scope of the experiment, the calculated value of the mathematical model is in good agreement with the experimental value.

1 INTRODUCTION

China's energy structure presents the resource endowment characteristics of "lack of oil, less gas and relatively rich coal" (Wang S M, 2021), and the coal-based energy consumption structure is difficult to change in a short time. In 2020, China's dependence on crude oil and natural gas will be 73% and 43%, and the security of energy supply has become an important factor restricting China's economic development (Ren L, 2019). Using coal pyrolysis to produce coal-based liquid fuels such as coal tar is an effective way to fill the gap in petroleum consumption and promote the efficient, clean and low-carbon utilization of coal (Li T, 2021). The coal pyrolysis process will produce a large amount of fine dust, resulting in poor oil quality and difficulty in further deep processing (Du X, Yang S Q). Moreover, dust deposition in tar will form tar residue that is difficult to deal with, thus leading to operation problems such as pipeline blockage and corrosion (Zhang Y Q, 2017). Granular bed filter has the advantages of high temperature resistance, corrosion resistance, high filtration efficiency and stable operating pressure, etc., and has great potential in high temperature dust removal (Yan S - Fan Y J).

In recent years, domestic and foreign scholars have carried out experimental research and mechanism exploration for granular bed filters. Chen Junlin et al. (CHEN Junlin, 2018) used CFD and DEM methods to fit the relationship between filtration efficiency and experimental operating parameters by using the empirical relationship of dust removal mechanism, but the model did not consider the influence of dust deposition and secondary dust removal. Liu Shuxian et al.(Liu S X, 2016) experimentally studied the factors affecting the filtration efficiency of granular bed filter and established the unsteady mathematical model. Yan Shen (Yan S., 2018) experimentally studied the effect of dust feed concentration and apparent gas velocity on filtration efficiency, and established a macro filtration model of granular bed filter.

At present, most of the macroscopic models of -granular bed filter filtration focus on the changes in the early stage of filtration, and cannot describe the filtration efficiency in the later stage of filtration, and most of the filter media with a smooth surface are used as the filtration medium. In order to reduce the cleaning cost of the granular bed filter and more accurately describe the change of filtration efficiency in the whole filtration process, this study took coal pyrolysis product semi-coke as the filtration medium and adopted a fixed granular bed to filter the powdered semi-coke in the gas. The mathematical model of unsteady filtration was established. Under different apparent gas velocity,

Wang, M.
Mathematical Modeling of Filtration Efficiency of Granular Bed Filter Based on Semi-Coke as Filter Medium.
DOI: 10.5220/0012286400003807

In *Proceedings of the 2nd International Seminar on Artificial Intelligence, Networking and Information Technology (ANIT 2023)*, pages 488-492
ISBN: 978-989-758-677-4

filter material thickness and filter material particle size, the variation rule of the model parameters of filtration efficiency is analyzed.

2 THEORETICAL CALCULATION OF FILTRATION EFFICIENCY OF PARTICULATE BED FILTER

The flow of dusty gas in the bed can be approximately regarded as one-dimensional flow, ignoring the axial and radial diffusion effects. The continuity equation under the granular bed filtration state is as follows:

$$u_s \frac{\partial c}{\partial y} + \frac{\partial \sigma}{\partial t} = 0 \tag{1}$$

The research of granular bed filtration usually starts from clean filter material, so the initial conditions and boundary conditions of its governing equation are:

$$c = 0, \sigma = 0 \quad (y \geq 0, t \leq 0) \tag{2}$$

$$c = c_{in}, \sigma = \sigma_i \quad (y = 0, t > 0) \tag{3}$$

When the dusty airflow passes through the granular bed filter, the dust concentration in the granular bed filter along the airflow movement direction obeys the exponential change law (Wang M, 2019):

$$\frac{\partial c}{\partial y} = -\lambda c \tag{4}$$

From formulas (1) and (4), it can be concluded that:

$$\frac{\partial \sigma}{\partial t} = \lambda u_s c \tag{5}$$

When Porous medium is used as the filter material, the dust will deposit on the surface of the filter material and in the bed gap during the filtering process, which changes the porosity of the entire bed, so the dust removal performance of the granular bed is affected. With the filtering process, the filtration coefficient λ It also changes accordingly, introducing a correction factor F=(σ), Indicates the degree of deviation of dust concentration in dusty gases during the filtration process(Bruno M W, 2014):

$$\lambda = \lambda_0 F(\sigma) \tag{6}$$

When considering the changes in the bed porosity and dust deposition on the filter surface, as well as the secondary entrainment phenomenon, the expression $F(\sigma)$ is:

$$F(\sigma) = (1 + b\sigma)^{n_1}(1 - a\sigma)^{n_2} \tag{7}$$

When $\partial\sigma / \partial t = 0$, that is, the accumulation of dust in the granular bed tends to be stable and reaches saturation $\sigma_{\max}$, where $a=1/\sigma_{\max}$. When b is larger, $F(\sigma)$ is larger, and the growth rate of σ with time is faster, and the filtration efficiency is higher. When a is larger, $F(\sigma)$ is smaller, the rate of decrease with time is faster, and the filtration efficiency is lower. Therefore, b represents the rising stage of filtration efficiency before the granular bed reaches saturation, that is, the accumulation process of dust; a represents the decreasing stage of filtration efficiency after the granular bed reaches saturation, that is, the penetration process of dust.

It can be obtained by formula (4) ~ (7):

$$\frac{\partial \sigma}{\partial t} = u_s \lambda_0 (1 + b\sigma)^{n_1}(1 - a\sigma)^{n_2} c \tag{8}$$

$$\frac{\partial c}{\partial y} - \lambda_0 (1 + b\sigma)^{n_1}(1 - a\sigma)^{n_2} c \tag{9}$$

Ives and Herzing et al. believe that there is the following relationship between dust concentration in the airflow and dust deposition density in the bed:

$$\frac{c}{c_{in}} = \frac{\sigma}{\sigma_i} \tag{10}$$

The partial derivative of formula (10) is obtained by substituting it into formula (9):

$$\frac{\partial \sigma}{\partial y} = -\lambda_0 (1 + b\sigma)^{n_1}(1 - a\sigma)^{n_2} \sigma \tag{11}$$

According to formula (8), the relationship between the dust deposition rate on the bed surface and time is as follows:

$$\frac{\partial \sigma_i}{\partial t} = u_s \lambda_0 (1 + b\sigma_i)^{n_1}(1 - a\sigma_i)^{n_2} c_{in} \tag{12}$$

Assuming that the filter material thickness is H and the experimental boundary conditions are: dust inlet concentration $c(0)=c_{\text{in}}$, outlet concentration $c(H)=c_{\text{out}}$, it can be obtained:

$$\int_{c_{in}}^{c_{out}} \frac{\mathrm{d}c}{c} = -\lambda_0 \int_0^H \mathrm{d}y \tag{13}$$

$$\lambda_0 = -\frac{\ln\left(\frac{c_{out}}{c_{in}}\right)}{H} \tag{14}$$

When the operating conditions in the filtration process are determined, the filtration efficiency of the particle bed filter is:

$$\eta = \frac{c_{in} - c_{out}}{c_{in}} \tag{15}$$

In the formula: u_{s} is the apparent gas velocity, m/s; c is the dust concentration of dusty gas, kg/m^3; σ is the dust deposition rate, kg/m^3; t is the filtering time, s; λ is the filtration coefficient, 1/m; $F(\sigma)$ is the correction factor; H is the filter material thickness, m; η is the filtration efficiency of granular bed filter.

The bottom corner marks in and out are the dust concentration at the inlet and outlet of the granular bed filter respectively.

3 EXPERIMENTAL PART

The cold experimental device of granular bed filter is shown in Figure 1, which mainly consists of a dust feeding device, an air supply device, a granular bed filter and a detection device. The dust is fed by a screw feeder and mixed with air at the inlet of the particle bed unit, and the dusty gas is separated by a granular bed filter.

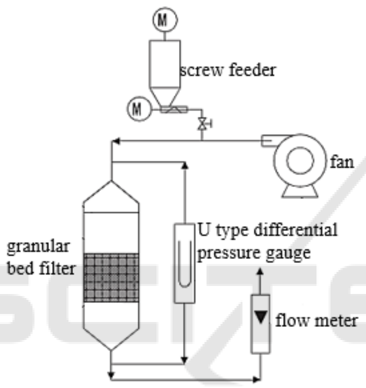


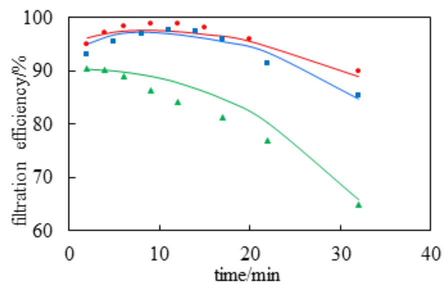
Figure 1: Experimental device for filtration characteristics of granular bed filter.

4 RESULTS AND DISCUSSION

In the calculation formula of filtration efficiency, n_1 and n_2 are adjustment parameters and have no specific physical significance. In order to study the influence of a and b on the filtration efficiency, n_1 and n_2 are set. In this study, when n_1=4 and n_2=1.3, the theoretical results have a good correlation with the experimental results.

4.1 Effect of Apparent Gas Velocity on Characteristic Constant of Filtration Efficiency Equation

The filter material thickness is 150 mm, and the filter material particle size is 0.83~ 1.25mm. Under different apparent gas velocities, Matlab programming software is used to fit the experimental data. The fitting curve is shown in Figure 2, and the characteristic constants of the equation are shown in Table 1.



Simulated value: — 0.25m/s; — 0.35m/s; — 0.50m/s;
Experimental value: ● 0.25m/s; ■ 0.35m/s; ▲ 0.50m/s

Figure 2: Fitting curves of filtration efficiency at different apparent gas velocities.

When the apparent gas velocity is 0.25 m/s, the maximum filtration efficiency of the granular bed filter for powdered semi-coke is 98.80%, and the average filtration efficiency is 96.57%; when the apparent gas velocity is 0.50 m/s, the maximum filtration efficiency of the granular bed filter is 90.39%, and the average filtration efficiency is 82.92%.

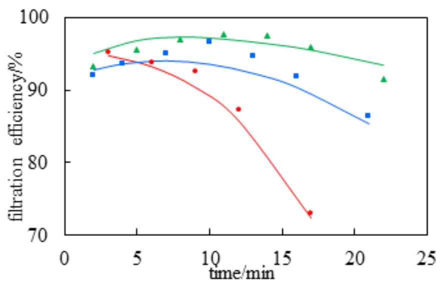
Table 1: Characteristic constants of filtration efficiency equation at different apparent gas velocities.

Apparent gas velocity/(m·s-1)	$\lambda 0$	a×105/(m3·kg-1)	b×105/(m3·kg-1)	$R2$
0.25	20.12	30.3	43	0.9935
0.35	17.91	42	39.80	0.9970
0.50	15.60	52	10	0.9973

As can be seen from Figure 2, in the rising stage of filtration efficiency, the larger the apparent gas velocity, the lower the filtration efficiency, that is, the smaller the b value. With the increase of apparent gas velocity, after the bed reaches saturation, the faster the filtration efficiency decreases, the lower the filtration efficiency, and the larger the a value.

4.2 Effect of Filter Material Thickness on Characteristic Constant of Filtration Efficiency Equation

The apparent gas velocity is 0.35 m/s, and the filter material particle size is 0.83~ 1.25mm. Under different filter material thickness, the fitting curve of filtration efficiency is shown in Figure 3, and the characteristic constants of the equation are shown in Table 2.



Simulated value: — 100mm; — 130mm; — 150mm;
Experimental value: ● 100mm; ■ 130mm; ▲ 150mm

Figure 3: Fitting curve of filtration efficiency under different filter material thickness.

When the filter material thickness is 100 mm, the maximum filtration efficiency of the granular bed filter for powdered semi-coke is 95.29%, and the average filtration efficiency is 88.38%. When the filter material thickness is 150 mm, the maximum filtration efficiency of the granular bed filter is 97.71%, and the average filtration efficiency reaches the maximum, which is 95.48%.

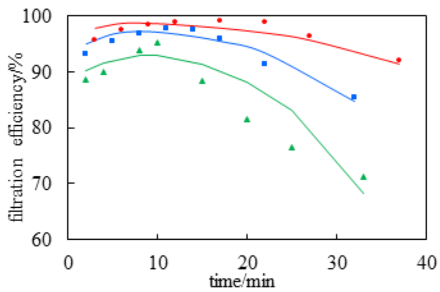
Table 2: Characteristic constants of filtration efficiency equation under different filter material thickness.

Filter thickness/(mm)	λ_0	$a\times10^5/(m^3\cdot kg^{-1})$	$b\times10^5/(m^3\cdot kg^{-1})$	R^2
100	30.5	51.50	6	0.9971
130	19	45.20	27.90	0.9973
150	17.91	42	39.80	0.9970

Before reaching bed saturation, the larger the filter material thickness, the higher the efficiency and the larger the *b* value; After the bed reaches saturation, with the extension of filtration time, the dust in the filter material will flow to the bottom of the bed under the scouring effect of the air flow, the greater the filter material thickness, the greater the probability of the dust washed by the air flow is intercepted by the bottom of the bed, so it is intercepted in the bed, therefore, the greater the filter material thickness, the smaller the *a* value.

4.3 Effect of Filter Particle Size on Characteristic Constant of Filtration Efficiency Equation

The apparent gas velocity is 0.25 m/s and the filter material thickness is 150 mm. Under different filter particle sizes, the fitting curve of filtration efficiency is shown in Figure 4, and the characteristic constants of the equation are shown in Table 3.



Simulated value: — 0.38~0.83 mm; — 0.83~1.25 mm; — 1.25~2.50 mm;
Experimental value: ● 0.38~0.83 mm; ■ 0.83~1.25 mm; ▲ 0.83~1.25 mm

Figure 4: Fitting curve of filtration efficiency under different filter size.

When the filter material particle size decreases from 1.25~ 2.50mm to 0.38~ 0.83mm, the maximum filtration efficiency of the granular bed filter increases from 95.26% to 99.08%, and the average filtration efficiency increases from 85.70% to 97.16%.

Table 3: Characteristic constants of filtration efficiency equation under different filter material particle size.

Filter size/(mm)	λ_0	$a\times10^5/(m^3\cdot kg^{-1})$	$b\times10^5/(m^3\cdot kg^{-1})$	R^2
0.38~0.83	21.10	35	40.46	0.9354
0.83~1.25	17.91	42	39.80	0.9970
1.25~2.50	14.50	47	33	0.9996

In the initial stage of filtration, the larger the filter material particle size, the lower the efficiency and the smaller the *b* value; The larger the filter material particle size, when the bed reaches saturation, the less the amount of dust accumulated in the bed, the larger the voidage, with the extension of the filtration time, the more easily the dust that has been captured to penetrate the bed with the air flow, the lower the filtration efficiency, so the larger the filter material particle size, the greater the *a* value.

5 CONCLUSION

Considering the changes in the porosity of the surface and bed of the porous media filter material, the filtration coefficient is introduced into the particle bed filtration model, and the model calculation is in good agreement with the experimental value. The model can provide a reference for the calculation of the filtration efficiency of the particle bed using porous media as filter material.

In the experimental range, reducing the apparent gas velocity and filter particle size and increasing the filter material thickness can increase the characteristic parameter *b* in the rising section of filtration efficiency, and reduce the characteristic parameter *a* in the falling section of filtration efficiency, so as to improve the filtration efficiency during the entire filtration time.

From the perspective of filtration efficiency of granular bed filter, the operating conditions can be selected as the apparent gas velocity of 0.25 m/s, the filter material thickness is 150 mm, and the filter material particle size is 0.38~0.83 mm. Under the experimental conditions, the filtration efficiency of the granular bed filter is 99.20%.

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