Development of the density distribution model in a gas-solid phase fluidized bed for dry coal separation

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Synopsis

The nature of the density distribution in a gas-solid phase fluidized bed for dry coal separation is an important factor in influencing the performance. However, during coal processing, fine slime would mix with dense medium of magnetite powder and accumulate in the bed, and its influence will affect the density of the bed. The mathematical model of the density distribution with fine slime behaviour was studied in an experimental laboratory system. The functional relationship between the density of the air dense medium fluidized bed and the coal slime content were fitted, applying the principle of least-squares method with damping factors. With the model, by analysing the trial testing data, the mechanism of the density distribution of the bed was studied and applied to a coal separation test with a pilot scale separator.

Keywords: dry coal separation, gas-solid phase, model fitting.

Introduction

The application of gas-solid phase fluidized bed technology for dry coal separation has been used commercially in China[1]. Traditionally, coal is separated from waste with water. However, in China, most of the coal mines are located in arid areas, and it is difficult to wash the coal with water. Additionally, some low-rank coals tend to turn to slime in wet processing.

The air dense medium fluidized bed dry coal separator uses gas-solid phases as the dense medium for coal separation, where the solid phase is magnetite powder. When fluidized, the state of the gas-solid phases of the bed performs like a fluid, and the heavy and light materials are separated by their densities.

There are several factors influencing the performance of the air dense medium fluidized bed separator. The stability of the fluidized dense medium and the distribution of the density stratification are two important factors in effecting the efficiency of separation. However, the coal slime content has a major impact on the characteristic of the density in the fluidized bed. Study of the density stability and its distribution in a laboratory device of the air dense medium fluidized bed and on a pilot scale separator would obtain basic parameters for density measurement and control in commercial air dense medium fluidized bed (ADMFB) coal plants[2].

Laboratory system

Density measurement

To measure the density of the air dense medium fluidized bed, a differential-pressure method was used. A density device was designed which included a pressure sensor, a monitor, a voltage amplifier and a digital AV meter. The density device shows the measured density on the monitor, and outputs a volt value for density control on the pilot scale fluidized bed and commercial separator.

A regression equation was obtained, using the differential-pressures of water as the standard values, by gauging the density device.

$$\Delta P = 39.989V - 0.776 \qquad [1]$$

where ΔP is the differential pressure, and V is the output voltage of the digital AV meter.

The average density of the air dense medium fluidized bed can be expressed as

$$\rho_{av} = \Delta P / H \cdot g \qquad [2]$$

where ΔP is the differential pressure, H is the height of the bed, g is gravity, and ρ_{av} is the average density of the bed[3,6]. Therefore if the voltage value of the density device can be read, it is possible to calculate the average density of the bed from Equations [1] and [2]. This correlation is useful for density measurement in the air dense medium fluidized bed.

Experimental fluidized bed

Under normal plant conditions for coal

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preparation in an air dense medium fluidized bed separator, fine slime coal would inevitably mix with the magnetite medium and enter the separator, which would impact on the density of the bed and affect separation[4]. Hence, the effect of fine slime in an air dense medium fluidized bed and its influence on the density distribution of the bed should be studied.

A laboratory scale 150 mm × 200 mm air dense medium fluidized bed was developed for studying the density characteristics and the density distribution (Figure 1). It consists of an air blower, a rotary flow meter, several throttle valves, two U shaped tubes, a density measuring device and an air dense medium fluidized bed.

The density device was designed and made specifically for measuring the density of the bed. The value of the pressure sensor is amplified and it can be read on a voltage meter. The device was initially scaled by means of differential-pressure and was mounted at points A and B of the bed. The two points are almost at the middle position of the column, and this position is usually the separating area of clean coal and rejects. The distance of A and B to the bed bottom is 280 mm and 180 mm respectively. Points C, D and E, F were also mounted on the fluidized bed. The distances of them to the bed bottom are 260 mm, 200 mm, 140 mm and 80 mm respectively. They are connected to two U shaped tubes to check the change of the density in the bed from layer by layer.

The fluidized bed is made up of an air chamber, an air distributor and a bed body. The air body is a column, which is filled with medium being measured. The area of the cross-section of the fluidized column is 200 mm × 150 mm. Its total height is 1000 mm, having a sectional joint in the middle for medium replacement. The bed body is made from organic glass. The distributor is made of a finely drilled plate or a sintered porous glass.

Test procedure

The required size of magnetic material is in the range of 0.15 mm~0.3 mm. Some research results have shown that the medium in the air dense medium fluidized bed could obtain an even and static condition when fine slimes, at a size range of 0.45 mm~0.9 mm, are mixed with magnetic particles[4,5].

Before every test, a certain amount of fine slime coal of the above size was mixed with magnetic material, shown in column (a) of Table I. When the bed is fluidized, read the voltage of AB on a voltage meter, and transmit it to an average density of the volume between A and B by Equations [1]) and [2]. It is named ρ_1. Secondly, the total height of the fluidized bed can be measured, and the initial weight of the added medium is known. Therefore, the average density of the bed, ρ_2, can be calculated from the weight of the medium divided by the volume of the fluidized medium[2]. For every level of the fine slime, twelve parallel tests were carried out. The calculated test data are shown on Table I.

Results

In Table I, column (d) is the average density of the fluidized bed, while column (c) is the density of volume between sectional planes A and B, which is located at the upper

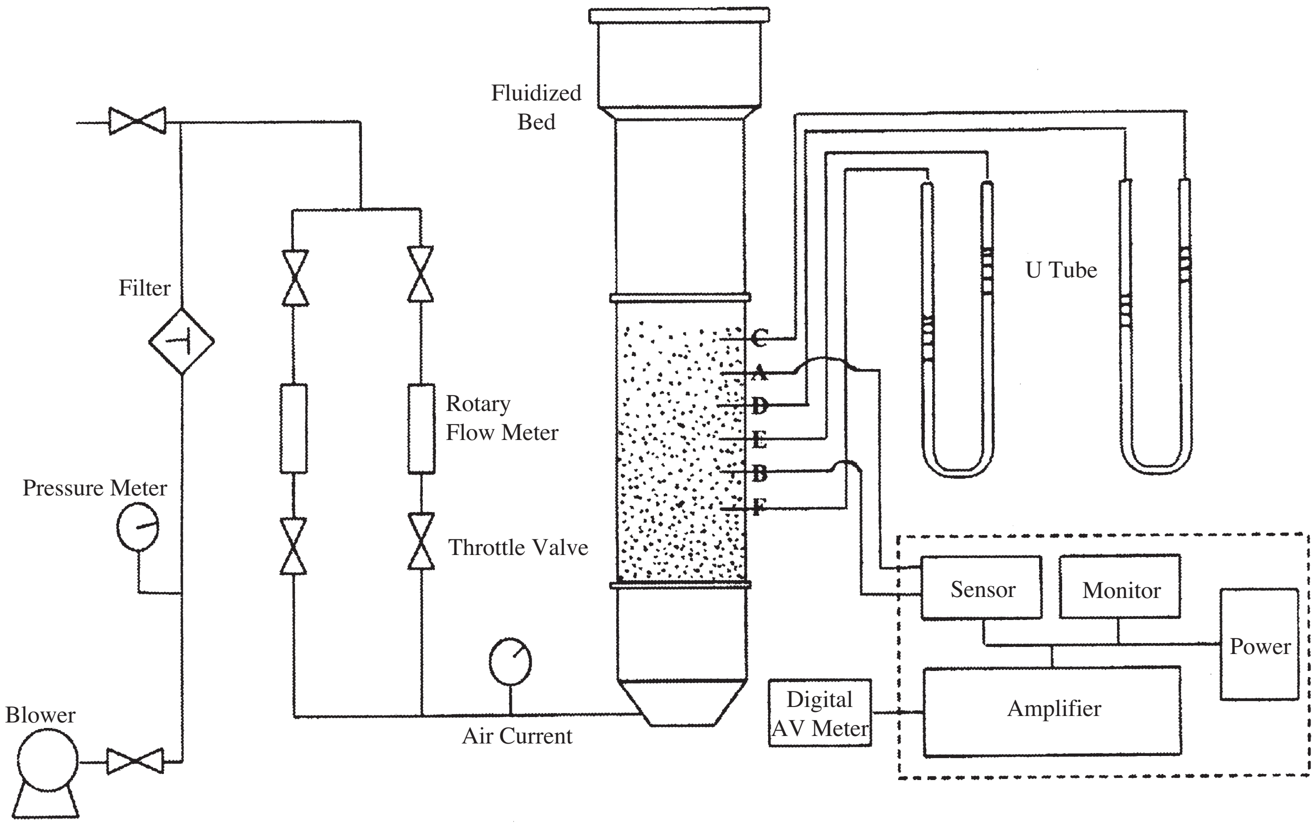

Figure 1—Laboratory system of air dense medium fluidized bed

Table I

Laboratory test data

No.	(a) Non-magnetic material (%)	(b) Bed height (cm)	(c) Density of AB (g/cm3)	(d) Average density of the bed (g/cm3)	(e) Air pressure (kg/cm2)	(f) flow rate (cm/s)
1	0.2	34.65	1.970	1.988	0.2	8.2
2	2.48	35.83	1.908	1.926	0.2	8.2
3	4.35	35.32	1.881	1.897	0.2	8.3
4	6.87	35.64	1.843	1.832	0.2	8.2
5	9.30	34.14	1.764	1.767	0.2	8.35
6	11.94	34.71	1.605	1.642	0.2	8.35
7	14.67	33.20	1.463	1.615	0.2	8.2
8	18.72	33.65	1.352	1.569	0.21	8.4
9	21.21	35.66	1.302	1.528	0.21	8.45
10	24.57	34.39	1.264	1.512	0.2	8.2
11	28.03	37.84	1.204	1.439	0.2	8.35

middle of the bed. By analysing Table I, we see that, when the percentage of fine slime contained in the fluidized medium is less than 12%, the average density of the bed and the density of the volume between sectional planes A and B is almost coincident. In this case, the density in the fluidized bed is generally in an even distribution, and the phenomenon of density stratification does not occur. When the percentage of fine slime is more than 12%, the appearance of bed stratification is increasing with the non-magnetic material proportion. When the percentage of fine slime in the fluidized medium is more than 18%, the difference between average density of the bed and the density between AB is approximately 0.2 g/cm^3.

Development of the density distribution model

Model fitting

To show that the density distribution in an air dense medium fluidized bed dry coal separator is influenced by slime content, the least-squares method with a damping factor was applied to simulate the density curve[7].

Supposing $Y=F(x)$ is a model function, $F(x)$ has m model parameters $r_1, r_2, \ldots, r_m$, and n is the number of the test data.

$$Let\ P = \sum_{i=1}^{n} \left(F(x_i) + \frac{\partial F}{\partial r_1}\Delta r_1 + \frac{\partial F}{\partial r_2}\Delta r_2 + \ldots + \frac{\partial F}{\partial r_m}\Delta r_m - y_i \right)^2 \qquad [3]$$

By minimizing P, applying $\Delta r_1, \Delta r_2, \ldots, \Delta r_m$ as the independent variables to calculate the partial derivatives, and assuming that the calculated derivative S equals zero, then

$$\left\{ \begin{array}{l} \sum_{i=1}^{n} \left(\frac{\partial F}{\partial r_1}\Delta r_1 + \frac{\partial F}{\partial r_2}\Delta r_2 + \ldots + \frac{\partial F}{\partial r_m}\Delta r_m \right) \frac{\partial F}{\partial r_1} = \sum_{i=1}^{n} FF(x_i)\frac{\partial F}{\partial r_1} \\ \hline \sum_{i=1}^{n} \left(\frac{\partial F}{\partial r_1}\Delta r_1 + \frac{\partial F}{\partial r_2}\Delta r_2 + \ldots + \frac{\partial F}{\partial r_m}\Delta r_m \right) \frac{\partial F}{\partial r_1} = \sum_{i=1}^{n} FF(x_i)\frac{\partial F}{\partial r_m} \end{array} \right. \qquad [4]$$

Where: $FF(x_i)=y_i-F(x_i)$, y_i are the observed test data. For calculating $\Delta r_1, \Delta r_2, \ldots, \Delta r_m$, it is necessary to solve the linear combination as follows.

$$\begin{bmatrix} \sum_{i=1}^{n}\left(\frac{\partial F}{\partial r_1}\right)^2, \sum_{i=1}^{n}\frac{\partial F}{\partial r_1}\cdot\frac{\partial F}{\partial r_2}, \ldots, \sum_{i=1}^{n}\frac{\partial F}{\partial r_1}\cdot\frac{\partial F}{\partial r_m} \\ \hline \sum_{i=1}^{n}\frac{\partial F}{\partial r_m}\cdot\frac{\partial F}{\partial r1}, \sum_{i=1}^{n}\frac{\partial F}{\partial r_m}\cdot\frac{\partial F}{\partial r_2}, \ldots, \sum_{i=1}^{n}\left(\frac{\partial F}{\partial r_m}\right)^2 \end{bmatrix} \cdot \begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \ldots \\ \Delta r_m \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} FF(x_i)\frac{\partial F}{\partial r_1} \\ \hline \sum_{1=1}^{n} FF(x_1)\frac{\partial F}{\partial r_m} \end{bmatrix} \qquad [5]$$

During the solution of the linear equation, to avoid the coefficient matrix becoming a 'sick' matrix, the diagonal values of which being infinitesimal, a damping factor α is added on its diagonal elements. The more times the calculation is repeated, the smaller the factor α will be, and at last it approaches zero.

For given $r_s,0$ $(s=1,2,\ldots,m)$ as the initial parameters, let $r_{s,k} = r_{s,k-1} + \Delta r_s$, where s is the number of times the calculations are repeated.

To find the solution, a mean square error E_f is applied between the test data and the theoretical values to judge if they are the satisfactory ones, otherwise the calculating procedure is repeated.

$$E_f = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - F(x_i)\right)^2}{n}} \qquad [6]$$

Density and slime content curve

From the above discussion, we understand that the content of fine coal slime in an air dense medium fluidized bed is the essential factor in influencing the density of the fluidized bed. It is important to study the density and slime content curve for controlling the density of the fluidized bed in commercial coal preparation plants. From sketching the density and slime content curve, it is noticeable that the relation of the density of the bed and the fine slime per cent

Table II

Fitted parameters of Equation [6]

	r_1	r_2	r_3	r_4	r_5	Error%
For the density between AS	2.8780	-0.2893	1.1964	-0.2862	5.5140	0.0274
For mean density of the bed	1.9153	2.0879	1.4302	-0.0962	4.7977	0.0280

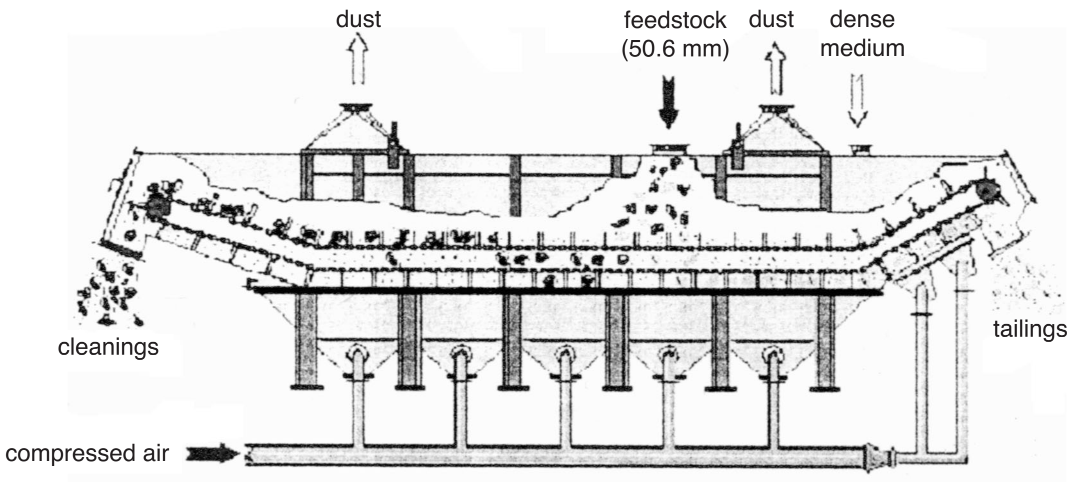

Figure 2—Pilot scale air dense medium fluidized bed separator

is a part of a normal distribution equation. For industrial controlling and application, we selected a modified normal distribution equation as a mathematical model, and the parameters of the curves are fitted.

$$\rho(x) = \frac{r_5}{\sqrt{2\pi r_1}} e^{-\frac{(r_4 - r_2)^2}{2r_1^2}} + r_3 \qquad [7]$$

where, ρ is a density of the bed, x is the percentage of non-magnetic material. Table II shows the fitted parameters of Equation [7].

Density distribution on ADMFB pilot scale separator

Horizontal density distribution

In a 5–10t/h air dense medium fluidized bed pilot scale separator (Figure 2), the sensors are arranged at three locations horizontally. The distance of each set to the clean coal end is 1700 mm, 2750 mm and 4300 mm separately. The last set is near the tailing end, and the distance to it is 1200 mm. Every set has three pairs of sensors, the distances of them to the bottom of the bed are 240 mm and 330 mm, 150 mm and 240 mm, 90 mm and 180 mm respectively.

In testing, two levels of percentage of non-magnetic material are applied. They are 14.2% of fine slime and 15.6% of fine slime in the medium of the fluidized bed pilot separator. The air pressure is 0.2 kg/cm^2, and the flow rate is 8.2 cm/s. For every test, six sets of data were read from the sensors. In Figure 3 and Figure 4, the curves with filled square marks express a lower layer density distribution, the cross-marked curves are the density of the middle layer, and the dot-marked curves refer to the upper layer density distribution.

From Figure 3 and Figure 4, we see that the density at the tailing end is higher than that at the clean coal end. The reason is that the light product is toward the clean coal end, while heavy product goes to the tailing end, so the mean density at the tailing end is high. By comparing and analysing the test data at different slime content, 14.2% and 15.6%, the results show that the differences of the mean densities between the tailing end and clean coal end are 0.066 g/cm^3 and 0.081 g/cm^3 respectively. With 15.6% fine slime in the bed, the test data shows that the upper layer makes stratification with the middle and the lower layer. This phenomenon is apparent between the upper layer and middle layer, and it is detrimental to the coal separation.

Vertical density distribution

By analysing the test data, we established the nature of the vertical density distribution at the clean coal end, middle section and tailing end of the air dense medium fluidized bed pilot scale separator. Figure 5 shows the vertical density distribution with 14.2% content of fine slime, while Figure 6 shows the vertical density distribution with 15.6% content of fine slime. In Figure 5 and Figure 6, the dotted curve means the density at the tailing end, the cross-marked curve is the density at the middle of separator, and the filled square line is the density at the clean coal end.

In Figure 6, it can be seen that in the vertical direction there is an apparent gradient at the clean coal end, middle section and tailing end. The difference of the mean density between the lower layer and upper layer is 0.068 g/cm^3. Furthermore, the test data shows that sometimes the middle layer density is even higher than the lower layer density. This density disturbance in some parts of the bed shows that when the content of fine slime is high, the density stability in

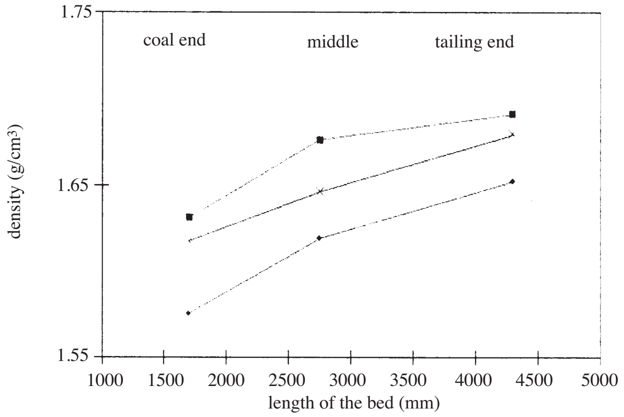

Figure 3—Density distribution with 14.2% slimes

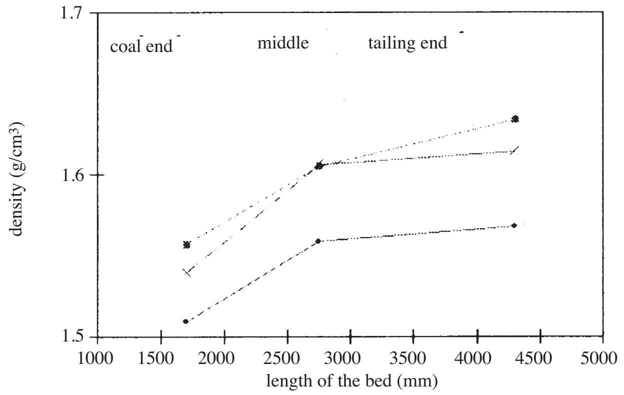

Figure 4—Density distribution with 15.6% slimes

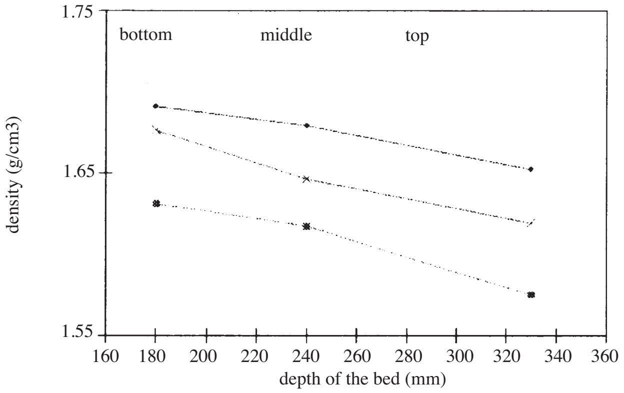

Figure 5—Vertical distribution with 14.2% slimes

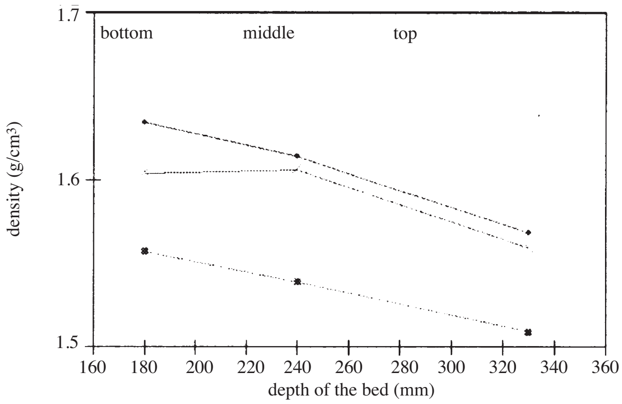

Figure 6—Vertical distribution with 15.6% slimes

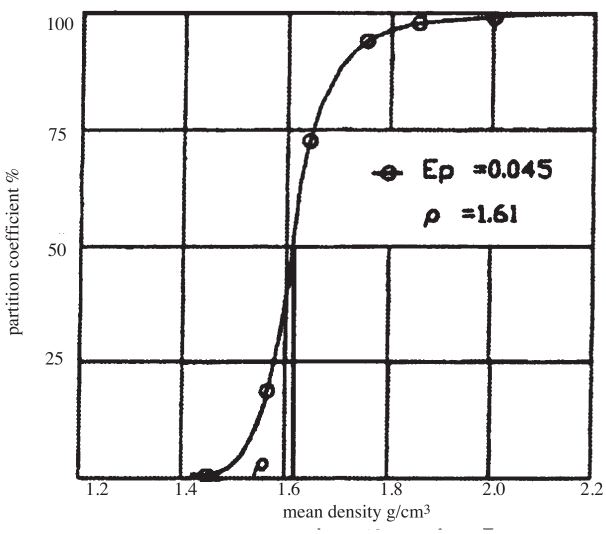

Figure 7—The partition curve of coal separation

the bed is unsatisfactory. For the bed with 14.2% of slime content, the mean density difference of the lower layer and the upper layer is 0.051 g/cm^3. There is no apparent density stratification, even at the clean coal end, and the density disturbing phenomenon does not appear. These results indicate advantages for coal separation in the bed.

Separation test

To investigate the density stability of the bed, a separation test was carried out using the 5 tph pilot scale separator feed coal of 50 × 6-mm. The feedstock coal was obtained from Xuzhou Coal Mine Bureau, Jiangsu Province of China. The bed density was maintained at 1.61g/cm^3 with a fine slime content of 14.2%. Figure 7 shows the partition curves of the two products. The probable error (Ep value) at the separation density 1.61g/cm^3 is 0.045.

The partition curve of the products indicates the good performance of a 5 tph pilot scale air dense medium fluidized bed separator with the fine slime content at 14.2%.

Conclusions

- A density device was designed and made for density measuring in the air dense medium fluidized bed, and a regression equation for density measuring was obtained.
- By analysing the test data, the functional relation between the density of the bed and the coal slime content was determined. The mathematical model provides a basis for density measurement and control in an industrial air dense medium fluidized bed dry coal separation system.

- ➤ The density distribution in an air dense medium fluidized bed pilot scale separator was studied horizontally and vertically. The density stratification phenomena were explained.
- ➤ A coal separation test was carried out on a 5 tons/h pilot scale air dense medium fluidized bed dry coal separator. Results showed it can efficiently separate 50*6-mm coal with an Ep value of about 0.045, when the fine slime content is 14.2%.

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