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Experimental research on drying characteristics of PVC powder in a normal fluidized-bed dryer

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Abstract: For obtaining the drying curve of powder under fluidized drying, a normal fluidized-bed dryer is designed to study the drying kinetics of PVC (polyvinyl chloride) powder in the experiment. A new measure system is derived for drying dynamics testing. In the small fluidized-bed dryer, fluidization parameter of PVC powder is tested, and the operating air velocity can be chosen in the range of 0.41 to 0.55 m/s. Accordingly, the fluidized number u_a/u_{mf} is from 1.24 to 1.67. A promising drying model is used to describe the drying process, and then the characteristic drying curve of PVC powder derived from a suspension method can be expressed as $f = \frac{-0.6226 + 1.2546\exp(2.5615\Phi - 0.7072)}{1 + \exp(2.5615\Phi - 0.7072)}$. Based on the experiments, the critical moisture content x_c and the mass transfer coefficient K are determined to be 0.02 kg/kg and 6.0×10^{-4} kg/(m^2·s), respectively. The experimental results in the small fluidized-bed dryer are similar to those of the real fluidized drying process, so the descried method can also be used in determining drying kinetics of powder materials such as PVC powder.

Key words: PVC; drying characteristics; critical moisture; mass transfer coefficient

Drying is one of the important unit operations. The mechanism of drying is very complex because heat and mass transfer exist simultaneously. The drying characteristics of materials are important for dryer design, and the critical moisture of material is one of the key parameters. Though the drying characteristics of materials are concerned with the type and nature of dried materials, it is also important to choose among the various drying methods and operation conditions. Based on experiments, various mathematical methods[1-9], including computer modeling, have been in studying drying kinetics for different materials in previous papers.

This paper is one of the basic researches for designing circulation-impinging stream drying processes and related equipment. In the drying process, an impinging zone is designed to enhance heat and mass transfer strongly, and various residence times of dried material are available by adding circulation of dried material in order to remove both free moisture and that in the pores of dried material in a dryer. The details of the dryer will be introduced in another paper. PVC produced by the suspension method is a typical porous material, and it is one of the main applied objectives of the designed drying device. So the drying characteristics of PVC powder are very important for the design.

It is essential that the kinetics experiment should proceed under the same conditions as the real drying device, and drying characteristics of materials can be similar to the real dryer. Such characteristics can also be achieved by engineering design. The drying curve measured by the direct-weighted method in the drying tunnel is imprecise because of the great moisture transfer resistance in the samples. The traditional drying tunnel method also results in greater critical moisture of the sampling material, so the measured drying characteristics cannot be used in fluidized drying[10]. On the other hand, the flow of particles is very complex in the designed dryer, and the drying characteristics are difficult to measure under real drying conditions, which is similar to real circulation-impinging stream drying. By analyzing the designed circulation-impinging stream drying process, it can be found that the moisture of a material can be removed in an acceleration tube and an impinging zone, and the drying process is similar to fluidized-bed drying. Therefore, a small circular fluidized-bed dryer is applied to study the drying kinetics of PVC powder.

1 Experimental Apparatus and Method

1.1 Experimental apparatus

Fig. 1 shows the operating scheme of a circular fluidized-bed dryer. Because of the poor fluidity of

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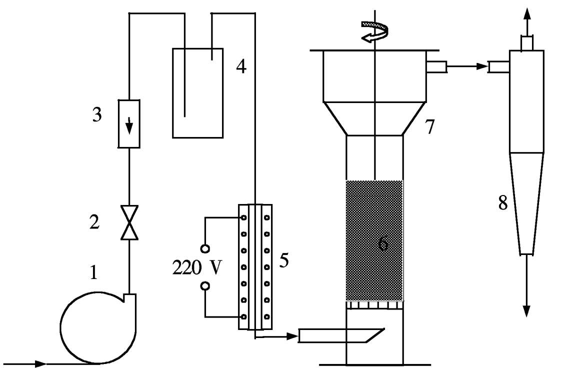
moisture PVC powder, a mixer is located in the fluidized-bed dryer to improve the fluidity of moisture PVC powder at the initial drying stage. The inlet air is introduced into the measure system by a fan. The velocity of the inlet air is adjusted by a cut-off valve and a rotormeter. Before being heated by a pre-heater, the inlet air goes through an air-saturated device to keep the moisture of heated air constant[11]. A cyclone is located at the outlet of the fluidized-bed dryer to collect small powder in the exhaust air. The initial loading of moisture PVC powder in the fluidized-bed dryer is very important, and it is chosen by several preliminary experiments. The initial loading depends on the flow state in the fluidized-bed dryer.



1—Fan; 2—Cut-off valve; 3—Rotormeter; 4—Air-saturated tank; 5—Air pre-heater; 6—Stirrer; 7—Fluidized-bed; 8—Cyclone

Fig. 1 The diagram of hydronamics mensurration

1.2 Experimental method

The drying kinetics testing is batch-operated in these experiments. The drying system is pre-heated by heated air until the temperature of the system does not change. After shutting off the heated inlet air, moisture PVC powder, of which the initial moisture is x_0, is put into the fluidized-bed dryer (see Fig. 1); and the heated air is introduced to fluidize the wet PVC powder. Samples are collected every 5 min after the flow state in the dryer remains stable, and the samples are dried in an oven at 150 ℃ until the weight of the samples does not change. The moisture of samples x can be calculated by the weight loss of samples. Therefore, the relationship between the moisture of samples x and time t can be plotted in the Descartes coordinate, and the critical moisture x_c can also be found at the turning point in the x-t curve.

Before these experiments, the dry PVC powder produced by the suspension method in Zhuhua Corporation, was re-wetted and stirred adequately, and the size of the wet PVC powder particles was smaller than 60 mesh according to the initial moisture. Also, the mixed wet PVC powder was airproofed up to 12 h in order that the added water could be transferred into the micro-pores of the PVC particles adequately, and water evaporation could be efficiently avoided at the same time.

2 Fluidization Parameter of PVC

For choosing the operating air velocity, fluidization parameters of PVC powder are determined before the drying experiments. The initial fluidized velocity u_{mf} is determined by using the traditional velocity-pressure method[12] in the fluidized-bed as shown in Fig. 1. The experimental results are shown in Fig. 2, and the initial fluidization velocity u_{mf} can be known as 0.33 m/s.

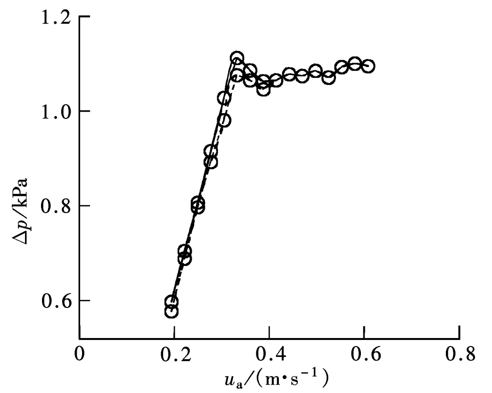


Fig. 2 The relationship between Δp and u_a in fluidized-bed

As a result, the operating air velocity is chosen in the range of 0.41 to 0.55 m/s, and accordingly the fluidization number u_a/u_{mf} is 1.24 to 1.67.

3 Results and Discussion

3.1 Experimental description

Due to the poor fluidity of wet PVC powder, channel flow occurs at the initial drying stage. Drying is not uniform at different places of the fluidized-bed without stirring, but it can cause slugging by increasing the inlet air flow. Introduction of a stirrer can disperse the agglomerated PVC particles efficiently enough to fluidize the wet PVC powder. During the drying process, the moisture of PVC powder decreases gradually; the fluidity of PVC powder is also observably improved, and bubbling can be observed at the end of drying. At the same time, the small powder in the exhaust air increases with drying. The powder in the exhaust air is about 5 % of total loading when the loading is 300 g, so a cyclone is introduced to collect powder in the outlet air, and the collected powder is added to the dryer again to ensure the validity of the samples.

3.2 Drying rate

Various x-t curves[13-14], tested on different operating air velocities and temperatures, are shown in Fig. 3. It can be found that the drying characteristics of PVC powder can be described by the two-period model, including constant rate drying period and falling rate drying period.

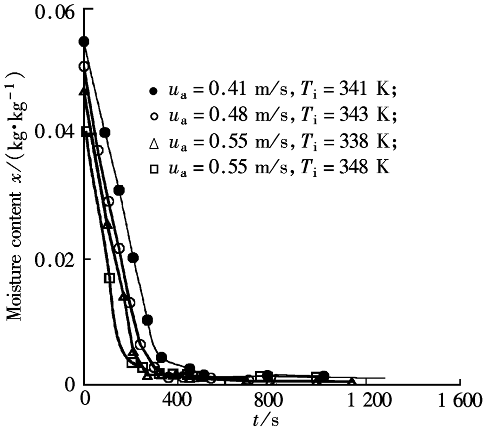


Fig. 3 The relationship between moisture of PVC and time

3.3 Critical moisture

Based on the turning point of the *x-t* curve in Fig. 3, it is convenient to find the critical moistures of various operating conditions, and the results are listed in Tab. 1. Also, the repetitiveness of the experiments in Tab. 1 is acceptable. Then, the mean value of the ten experiments is 0.02 kg/kg, which is critical moisture in suspension drying for engineering application.

Tab. 1 The critical moisture of PVC

Number	Air temperature/K		u_a/	x_c
	Dry bubbe	Moisture bubble	$(\mathrm{m \cdot s^{-1}})$	$/(\mathrm{kg \cdot kg^{-1}})$
V1-1	338.15	301.65	0.55	0.020 3
V1-2	356.15	304.85	0.55	0.021 0
V1-3	348.15	304.05	0.55	0.020 1
V1-4	348.15	304.05	0.55	0.021 1
V1-5	338.15	301.45	0.55	0.016 4
V1-6	336.65	301.05	0.55	0.020 9
V2-1	341.15	303.15	0.41	0.021 3
V2-2	343.15	303.55	0.41	0.019 8
V3-1	344.65	304.95	0.48	0.021 0
V3-2	343.15	304.65	0.48	0.017 3

Notes: The mean value of x_c by ten experiments is 0.02 $\mathrm{kg \cdot kg^{-1}}$, and the initial moisture of PVC is lower than 5%.

3.4 Drying characteristic curve of PVC

It is difficult to obtain the drying rate during falling-rate drying for analysis and drying process design. Due to the complexity of the drying mechanism, various models are developed to describe the drying kinetics. A promising method is used to define the relative drying rate *f*,

$$f = \frac{N}{N_w} \tag{1}$$

and the drying rate per surface area can be expressed as

$$N = fN_w = fK\phi(Y_w - Y_g) \tag{2}$$

The value of the relative drying rate *f* depends on the extent to which drying has occurred; for the material, *f* can be described by the two-period drying model. *f* can be expressed as

$$f = \begin{cases} 1 & x \geqslant x_c \\ f(\Phi) & x < x_c \end{cases} \tag{3}$$

where Φ is the characteristic moisture content, or called the relative free moisture content, and it is defined as

$$\Phi = \frac{x - x^*}{x_c - x^*} \tag{4}$$

For PVC, equilibrium moisture content x^* can be approximately 0 kg/kg.

Based on experimental data N, N_w and f of every different moisture content, x, can be obtained by using the figure-differential method in the smoothing *x-t* curves, and corresponding Φ can also be calculated by Eq. (4). Results show that similar to the drying kinetics of wool[15], various types of relationships between *f* and Φ exist because of unknown random factors. But most experiments can obtain the same type of results as shown in Tab. 2, and repeat of data is acceptable for complex heat and mass transfer processes of porous material. The statistical mean values of six experimental data are shown in Fig. 4 by solid cycle.

Tab. 2 The values of *f* and Φ

Φ	*f*						
	1	2	3	4	5	6	Mean
0.1	0.105	0.102	0.103	0.103	0.122	0.108	0.107
0.2	0.211	0.202	0.218	0.212	0.272	0.217	0.224
0.3	0.320	0.332	0.340	0.313	0.433	0.333	0.345
0.4	0.457	0.432	0.440	0.433	0.557	0.458	0.463
0.5	0.595	0.532	0.538	0.580	0.650	0.577	0.579
0.6	0.695	0.630	0.635	0.735	0.733	0.683	0.685
0.7	0.782	0.725	0.737	0.835	0.813	0.775	0.778
0.8	0.863	0.818	0.833	0.903	0.887	0.858	0.860
0.9	0.935	0.913	0.927	0.955	0.967	0.933	0.938
1.0	1	1	1	1	1	1	1

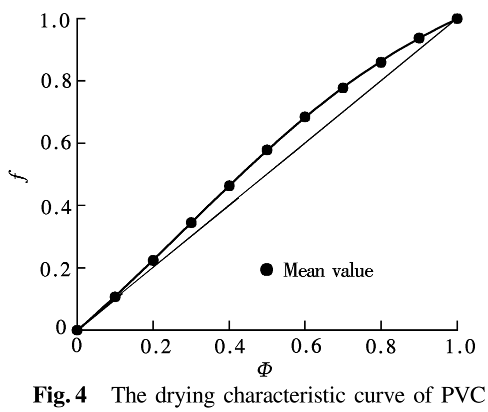


Fig. 4 The drying characteristic curve of PVC

For convenience, the characteristic drying curve in Fig. 4 can be represented by a continuous-analytic function:

$$f=\frac{-0.6226+1.2546\exp(2.5615\Phi-0.7072)}{1+\exp(2.5615\Phi-0.7072)} \quad (5)$$

Calculated results are also shown by real line in Fig. 4. The correlation coefficient is 0.999 9 in Eq. (5), which is suitable for engineering application.

3.5 Mass transfer coefficient

Mass transfer coefficient K can be calculated by

$$K=\frac{N_w}{\phi \Pi_{lm}} \quad (6)$$

where Π_{lm} is the logarithmic humidity potential. It can be expressed as

$$\Pi_{lm}=\frac{\Pi_{in}-\Pi_{out}}{\ln(\Pi_{in}-\Pi_{out})} \quad (7)$$

And humidity potential can be defined as

$$\Pi = Y_w - Y_g \quad (8)$$

ϕ is the dimensionless humidity potential coefficient, and it can be expressed as

$$\phi=\frac{0.622}{0.622+Y_m} \quad (9)$$

where

$$Y_m=\frac{\bar{Y}_g+Y_w}{2} \quad (10)$$

$$\bar{Y}_g=\frac{Y_{g,in}+Y_{g,out}}{2} \quad (11)$$

N_w is the surface drying rate of a constant rate drying period, and it is expressed as

$$N_w=-\frac{m}{A}\frac{dx}{dt} \qquad dx<0 \quad (12)$$

where m is the weight (dry base) of a sample, and the total surface of the sample can be calculated by

$$A=\frac{6m}{\rho_p d_p} \quad (13)$$

By preliminary experiments, $\rho_p = 947.3\ kg/m^3$, and $d_p = 0.18$ mm.

The calculated results of ten experiments are shown in Tab. 3. It can be found that K varies remarkably with drying conditions. A possible explanation is that the surface and the internal temperature of the dried material keep constant at the beginning of the falling-rate drying period. The surface convection mass and heat transfer coefficients are a function of surface moisture content. If further drying proceeds, surface moisture content will be less than the maximum rudimental moisture content, and the dry zone will appear on the surface of material. Then moisture transfer will proceed in some very thin capillary, the temperature of the dried material will be raised at the same time, so the drying dynamic will be strongly concerned with drying conditions at this time[16]. Further research is required to carry out the quantitative analysis of the data in Tab. 3, but reappearance of the data can be acceptable for engineering applications. Therefore, based on the data in Tab. 3, recommendatory mean mass transfer coefficient in suspension drying K is 6.0×10^{-4} $kg/(m^2\cdot s)$.

Tab. 3 The result of mass transfer coefficients

Number	$K/(kg\cdot m^{-2}\cdot s^{-1})$	Number	$K/(kg\cdot m^{-2}\cdot s^{-1})$
V1-1	5.921×10^{-4}	V1-6	7.028×10^{-4}
V1-2	9.630×10^{-4}	V2-1	5.758×10^{-4}
V1-3	3.768×10^{-4}	V2-2	7.046×10^{-4}
V1-4	4.509×10^{-4}	V3-1	4.648×10^{-4}
V1-5	6.080×10^{-4}	V3-2	5.476×10^{-4}

4 Conclusion

By knowing the limitations of the traditional drying dynamics testing methods, in this paper, a circular fluidized-bed dryer is designed. A new drying system is derived to study the drying characteristics of PVC powder produced by the suspension method. In choosing the experimental conditions, fluidization parameters of PVC powder in the fluidized-bed dryer is preliminary tested; the operating air velocity is chosen in the range of 0.41 to 0.55 m/s, and accordingly the fluidized number u_a/u_{mf} is 1.24 to 1.67. The characteristic drying curve of PVC powder produced by the suspension method can be expressed as $f=\frac{-0.6226+1.2546\exp(2.5615\Phi-0.7072)}{1+\exp(2.5615\Phi-0.7072)}$. Based on the experiments, x_c and K are determined to be 0.02 kg/kg and 6.0×10^{-4} $kg/(m^2\cdot s)$, respectively. The experimental results in the small fluidized-bed dryer are similar to those of the real fluidized drying process, so the method described in this paper can also be used in determining drying kinetics of powder materials such as PVC powder.

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流化床中 PVC 粉末干燥特性研究

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摘要: 为了获得流态化干燥状态下的粉体干燥曲线,设计了一种小型流化床干燥装置用于粉体材料的干燥特性测定. 应用该装置,实验研究了悬浮法 PVC 粉体的干燥特性. 测定的 PVC 粉体在该流化床中流化参数为操作气速介于 0.41 ~ 0.55 m/s 之间,即流化数 u_a/u_{mf} 为 1.24 ~ 1.67. 实验测定了 PVC 粉体干燥动力学曲线,回归得到描述 PVC 干燥特性曲线的解析函数为 $f = \dfrac{-0.6226+1.2546\exp(2.5615\Phi-0.7072)}{1+\exp(2.5615\Phi-0.7072)}$. 确定了实验条件下 PVC 干燥的临界湿含量 x_c 及传质系数 K 分别为 0.02 kg/kg 和 6.0×10^{-4} kg/(m^2·s). 由于实验方法比较接近工业流态化干燥过程,获得的结果对于工程应用较为可靠,该方法可用于如 PVC 一样的粉体材料的干燥特性测定.

关键词: PVC; 干燥特性; 临界湿含量; 传质系数

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