

# Characteristics of a Flow Transducer Based on Polarized Charge<sup>\*</sup>

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**Abstract:** In this paper we analyze the characteristics of a flow transducer based on polarized charge. The effects of the charged particles in pneumatic pipeline on the measurement pipe potential are discussed in detail and the equivalent circuits of the potential measurement are presented. On this bases, the relationships between mass flowrate and the electrical potential are obtained for different time constants of the measurement circuit. A satisfactory model is presented based on the characteristics of gas-solid two-phase flow. The linearity of the model is verified by the experiment results. The transducer, which is coaxially connected with the transport pipeline, does not disturb the flow state and has the features of ruggedness and durability, it is especially suitable for industry process control.

**Key words:** polarized charge, gas-solid two-phase flow, measurement model

Pneumatic transportation of pulverized material plays an important role in many industries, such as electric power industry, chemistry industry and food-processing industry, etc. In order to improve the efficiency of plant control and operation, it is necessary to make a continuous, on-line measurement of mass flowrate of pulverized material travelling in the pipeline. The flow produced by pneumatic conveying of pulverized material is essentially a gas-solid two-phase mixture, and it is usually difficult to measure the flow parameters, because the movement of solid particles pneumatically conveyed in the pipeline is rather complex<sup>[1]</sup>. So far there is no satisfactory method to measure the flowrate of solid particles in a gas carrier<sup>[2-4]</sup>. The measurement based on polarized charge is a kind of innovative electrostatic method. By means of this idea, we can obtain a stable relationship between mass flowrate and the electrostatic charge. In this paper a mathematical model of mass flowrate measurement is presented and the experiments show that there exists a satisfactory linear relationship between the mass flowrate and the output voltage.

## 1 Configuration of the Transducer

The transducer is shown in Fig.1. It consists of measurement probe, power supply unit and signal preprocessing unit, and the measurement probe is a key part of the transducer. It mainly consists of three parts: initialization pipe section, charging pipe section and measurement pipe section. They are insulated from each other by dielectric pipe sections. The transducer has the same inner diameter as the pneumatic

transportation pipe, and they are connected coaxially. The upriver initialization pipe is used to neutralize charges on the surface of pulverized material, which are generated by triboelectric effect during the pipe line transportation before the material enters the charging pipe. A high electric potential is applied on the charging pipe section, generating electric field. The solid particles are polarized when passing through the electric field, and the polarized charge per unit cubage is proportional to concentration of the particles. When the charged material enters the measurement pipe section, the potential is generated on the measurement pipe due to electrostatic induction and collision. After pre-processing and A/D conversion, the digitized potential signal is input to the computer.

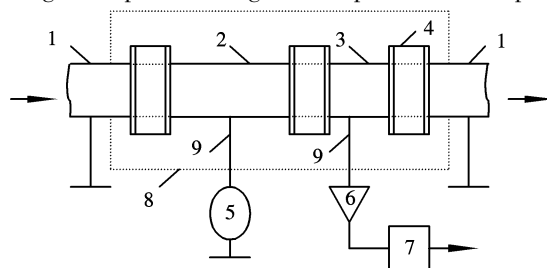


Fig.1 Mass flowrate transducer.

1. Initialization pipe section; 2. Charging pipe section;
3. Measurement pipe section; 4. Dielectric pipe section;
5. Power supply of charging pipe section; 6. Preamplifier;
7. A/D converter; 8. Metal cover; 9. Shielded cable

## 2 Characteristics of the Transducer

### 2.1 The charging pipe

When pulverized material travels through the

electric field in the pipe, it is charged due to electrostatic induction and collision<sup>[5,6]</sup>. The quantity of charge is determined by the dimension of the measurement probe, the potential applied to the charging pipe and the features of the pulverized material. Suppose there is a dielectric ball in electric field, then the polarized charge on its surface is

$$q = kr^2E \quad (1)$$

where  $k$  is a coefficient;  $r$  is the radius of the dielectric ball;  $E$  is the electric field intensity.

The charged particles traveling in pipe form a charge flow. Assume the space density is radially symmetric, and the equivalent radius of the particles is  $r$ , then the charge flow rate is

$$Q(t) = \frac{3qm(t)}{4\pi r^3 \gamma} = \frac{3kE}{4\pi r \gamma} m(t) \quad (2)$$

where  $m(t)$  is the mass flowrate of the particles;  $\gamma$  is the density of the particles. Accordingly, the space density of charge at the entrance of measurement pipe is

$$\rho_0(t) = \frac{Q(t)}{\pi R^2 v} = \frac{3kE}{4\pi^2 r R^2 \gamma v} m(t) \quad (3)$$

where  $R$  is the inner radius of the pipe;  $v$  is the velocity of the solid particles.

## 2.2 The measurement pipe

There are two phenomena to appear when the charged particles enter the measurement pipe section. One is the electrostatic induction. The metal measurement pipe is just like a kind of Faraday pail, the inductive charge is generated on its surface when there is net charge in the pipe and meanwhile a potential is built up on the measurement pipe. The other is charge leakage. A part of charges on the particles is delivered to the measurement pipe by the collision of the particles with the inner surface of the pipe and leaks into ground via measurement devices, thus generates leakage current. This current also builds up a potential on the measurement pipe. In consequence, the total potential is the sum of potentials generated by the two effects.

### 2.2.1 The model of electrostatic induction

Charged particles travelling in a pneumatic pipeline form a flux, which has the shape of a column similar to that of an interior of the pipe, let the cross-sectional area of both the column and pipe be identical and constant in the whole measuring zone, and both the cross-sections have the circular shape. The charges produce an electric field that varies with time randomly and is radially symmetric. Thus the metal pipe is charged by electrostatic induction under

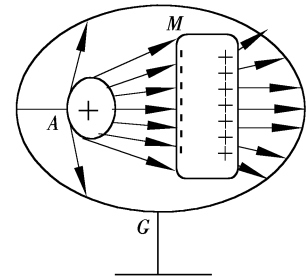
the action of this field. In consequence an electric potential is built up on the pipe and also varies with time, as does the space density of charge.

The following fundamental assumptions have been made to enable derivation of the relationships between the potential and charge or its space density.

- The charging pipe is well electrically connected to the ground;
- Neglecting the effect of the high potential on the measurement pipe. This effect may be eliminated in the measurement circuit;
- All the mutual capacitances of the system are sensibly constant;
- The resistances between measurement pipe, sensing zone, and shield screen may be neglected;
- Any magnetic action of the charge may be neglected;
- The flow of particles in the pipe is a fully developed turbulent one.

The above assumptions permit one to obtain time functions in a concise and analytical explicit form that is convenient to undertake a further analysis of the measurement pipe.

A three-electrode system of charged bodies is analyzed to find out the relationships between the measurement pipe potential and the space density of particle charge. The system consists of a net electric charge in the sensing zone, a charge induced measurement pipe section, and a shield screen including the charging pipe section. The system is schematically drawn as Fig.2, where  $A$  is the electric charge carried by particles in sensing zone. Most of the electric field lines starting from  $A$  enter the measurement pipe  $M$ , and the rest enter shield screen  $G$ . The field lines entering  $M$  will leave  $M$  entirely. All the field lines enter grounded shield screen  $G$  at last.



**Fig.2** Schematic diagram of the three-electrode system.  $A$  is the net charge;  $M$  is measurement pipe;  $G$  is grounded shield screen

The potential on the measurement pipe should be sent to a measurement device, such as preamplifier, then the measurement model of electrostatic induction may be described by an equivalent circuit diagram as

shown in Fig.3, where  $q_1(t)$  is the net charge in the sensing zone;  $C_1$ ,  $C_2$  are capacitances among  $A$ ,  $M$  and  $G$ ;  $C_3$  is the total capacitance including the capacitance of measurement pipe with respect to the grounded shield screen, the capacitance of the wire and the input capacitance of a measurement device, e.g. preamplifier;  $R_3$  is the total resistance that consists of the measurement pipe leakage resistance, the insulation resistance of electric wire and the input resistance of measurement device. Suppose the initial conditions are zero, and then the Laplace transform relationship formula is

$$U_{01}(s) = \frac{C_2 R_3 s}{(C_2 \tau_3 + C_1 \tau_3 + C_1 C_2 R_3)s + C_1 + C_2} Q_1(s) \quad (4)$$

where  $\tau_3 = R_3 C_3$  is the time constant of measurement circuit. Consider that under usual dimensions of the transducer,  $C_1 \approx 0$ , thus Eq.(4) can be simplified as follows:

$$U_{01}(s) = \frac{R_3 s}{\tau_3 s + 1} Q_1(s) \quad (5)$$

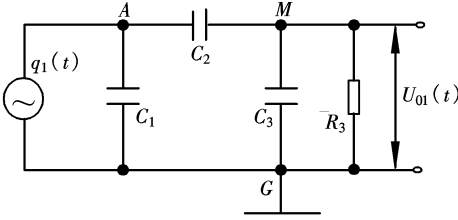


Fig.3 Equivalent circuit diagram of electrostatic inductive potential measurement

### 2.2.2 The model of leakage current

The charged particles travelling in the measurement pipe collide against the inner surface of the pipe, deliver part of their charges to the pipe, and form a leakage current  $i_2(t)$ . This current generates potential on the measurement pipe. Assume that the capacitance between sensing zone, measurement pipe and shield screen can be neglected. Then the equivalent circuit of leakage current measurement can be drawn as Fig.4. Under zero initial conditions, the relationship between  $u_{02}(t)$  and  $i_2(t)$  in Laplace transform is

$$U_{02}(s) = \frac{R_1 R_3}{(R_1 + R_2) \tau_3 s + R_1 + R_2 + R_3} I_2(s) \quad (6)$$

Consider the same transducer as above, then  $R_1 \approx \infty$ , and Eq.(6) can be simplified as

$$U_{02}(s) = \frac{R_3}{\tau_3 s + 1} I_2(s) \quad (7)$$

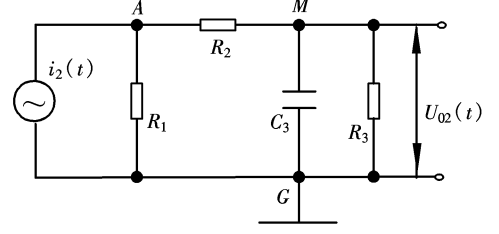


Fig.4 Equivalent circuit diagram of leakage current measurement

### 2.2.3 The relationship of measurement pipe potential — charge density

Assume that sensing zone has the same radius  $R$  and length  $L$  as the measurement pipe; and in the sensing zone the particle concentration is radially symmetric; the space density of charge decreases exponentially as follows:

$$\rho(l) = \rho_0(t) e^{-\frac{l}{\tau}} \quad 0 \leq l \leq L \quad (8)$$

where  $\tau$  is charge leakage time constant, then the net charge in the sensing zone is

$$\begin{aligned} q_1(t) &= \int_0^L \rho(l) \pi R^2 dl = \pi R^2 \nu \tau (1 - e^{-\frac{L}{\tau}}) \rho_0(t) \\ &= k_1 \rho_0(t) \end{aligned} \quad (9)$$

The leakage charge in the sensing zone is

$$\begin{aligned} q_2(t) &= \pi R^2 L \rho_0(t) - q_1(t) \\ &= \pi R^2 (L - \nu \tau + \nu \tau e^{-\frac{L}{\tau}}) \rho_0(t) \end{aligned} \quad (10)$$

Accordingly the average leakage current of the sensing zone is

$$\begin{aligned} i_2(t) &= \frac{\nu q_2(t)}{L} = \frac{\nu \pi R^2}{L} (L - \nu \tau + \nu \tau e^{-\frac{L}{\tau}}) \rho_0(t) \\ &= k_2 \rho_0(t) \end{aligned} \quad (11)$$

In consequence, the potentials obtained respectively by two effects in Laplace transform are

$$U_{01}(s) = \frac{k_1 R_3 s}{\tau_3 s + 1} \rho_0(s) \quad (12)$$

and

$$U_{02}(s) = \frac{k_2 R_3}{\tau_3 s + 1} \rho_0(s) \quad (13)$$

Finally the total potential generated by charged particles is

$$\begin{aligned} U_0(s) &= U_{01}(s) + U_{02}(s) \\ &= \frac{k_1 R_3 s + k_2 R_3}{\tau_3 s + 1} \rho_0(s) \end{aligned} \quad (14)$$

There are three cases to be considered

$$1) \quad |\tau_3 s| \approx 1$$

$$\begin{aligned} u_0(t) &= \frac{R_1}{C_3} \rho_0(t) \\ &+ \left( \frac{k_2}{C_3} - \frac{k_1}{C_3 \tau_3} \right) e^{-\frac{t}{\tau_3}} \int_0^t e^{\frac{x}{\tau_3}} \rho_0(x) dx \end{aligned} \quad (15)$$

$$2) \quad |\tau_3 s| \gg 1$$

$$u_0(t) = \frac{k_1}{C_3} \rho_0(t) + \frac{k_2}{C_3} \int \rho_0(t) dt \quad (16)$$

$$3) \quad |\tau_3 s| \ll 1$$

$$u_0(t) = k_1 R_3 \rho_0'(t) + k_2 R_3 \rho_0(t) \quad (17)$$

### 2.3 The relationship of measurement pipe potential — mass flowrate

The pipe flow of charged particles is a complex stochastic process, and the average value of  $m'(t)$  can be approximately considered to be zero. For above three cases the last one is the most concise and is selected to measure pipe flow of solid particles. Put (3) into (17), we have the following equation

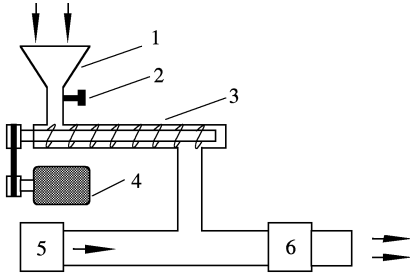
$$\begin{aligned} u_0(t) &= \frac{3kE\tau R_3(1 - e^{-\frac{L}{v\tau}})}{4\pi r\gamma} m'(t) \\ &\quad + \frac{3kER_3(L - v\tau + v\tau e^{-\frac{L}{v\tau}})}{L} m(t) \\ &= k_3 m'(t) + k_4 m(t) \end{aligned} \quad (18)$$

and the average value of potential is

$$\begin{aligned} \langle u_0(t) \rangle &= k_3 \langle m'(t) \rangle + k_4 \langle m(t) \rangle \\ &= k_4 \langle m(t) \rangle \end{aligned} \quad (19)$$

## 3 Experiment Results

The experimental device is shown in Fig.5. The pulverized coal is put into hopper, it falls down through apron to the screw feeder. The particle flow rate may be adjusted by the motor speed. The particles are



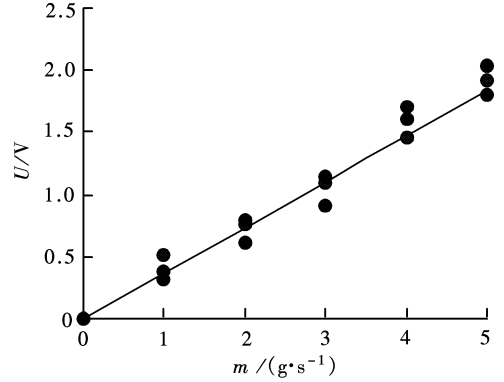
**Fig.5** Pneumatic transportation system of pulverized material.  
1. Hopper; 2. Apron; 3. Screw pulverized material feeder;  
4. Motor; 5. Blower; 6. Mass flowrate transducer

mixed with the high speed air generated by blower, thus form a so-called gas-solid two-phase flow. After a distance of transportation, the flow state becomes steady, and then it enters measurement probe.

A high potential is applied on the charging pipe to charge the pulverized material. The polarity and quantity of the charge yielded on the measurement pipe are determined by the polarity and amplitude of the high potential. The sensitivity of the transducer is proportional to this potential. To improve signal/noise ratio, the sensitivity of the transducer should be high enough, i.e., the potential applied should maintain at a relatively high level. On the other hand, the

potential cannot be too high, which may cause the explosion of pulverized coal. So, the potential should be set properly. Experiments show that when this potential reaches 100?V, the polarizing phenomenon can be observed. And there is no discharging to be found when it reaches 500?V.

In the measurement system, the diameter of the measurement probe is 40?mm, the length of charging pipe is 160?mm, the length of measurement pipe is 80?mm and the length of dielectric pipe is 10?mm. The sampling rate is 2?kHz and the sample length is 10?s. Fig.6 shows the measurement results where the high potential is 300?V. The tests show that the output of transducer is linear with the mass flowrate.



**Fig.6** Measurement result, output voltage vs. mass flowrate

## 4 Conclusion

There exists a linear relationship between the mass flowrate and the output of the transducer. Eq. (19) is quite a good mathematical model for the continuous mass flowrate measurement. The linearity of the model is very important and useful for further study and developing new mass flow measurement device. In addition, the transducer does not disturb the flow state in pipe and has the features of ruggedness and durability, it is especially suitable for industry process control.

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基于极化电荷的流量传感器特性

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**摘 要** 对基于极化电荷的流量传感器特性进行了比较系统深入的分析,详细讨论了荷电颗粒对测量管电势的影响,给出了等效测量电路,针对测量回路时间常数的不同情况,得到了质量流量与输出电势之间不同的关系式,并根据气固两相流的特性得出了令人满意的测量模型.实验结果验证了模型的线性特性.基于极化电荷的流量传感器不仅结构简单、寿命长,而且与气输管道同轴密封连接,不影响粉粒体在管道中的流动状态,因此特别适合于工业过程控制.

**关键词** 极化电荷, 气固两相流, 测量模型

**中图分类号** TM930.12