Review of gas-solid two phase flow rate-concentration detection technology

LIU Xiu[1], LIU Ji[1,2], ZHANG Jing[1], YAN Bing[2], SHI Lu-lu[1]

(1. *Science and Technology on Electronic Test & Measurement Laboratory, North University of China, Taiyuan 030051, China*;
2. *School of Information and Communication Engineering, North University of China, Taiyuan 030051, China*)

Abstract: The indirect detection method basic principle of rate and concentration, application range and research results on gas-solid two phase flow were discussed. The present development situation and the existing problems of rate and concentration detection technology were analyzed and summarized. Emphatically analyzed the existing problems in the industrial application and research status of electrostatic method in measuring phase concentration. Design criterion of electrostatic phase concentration sensor is given, the superiority and wide industrial application prospect of the sensor used for phase concentration measurement are clarified.

Key words: gas-solid two phase flow; rate-concentration; electrostatic method

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0 Introduction

Pneumatic transport of solid materials technology is widely applied in the actual engineering process, gas-solid two phase flow has become one of the most common and important forms of multiphase flow in the pneumatic transmission pipeline. In the food and chemical industry production process, for example, accurate rate measurement of two phase flow can effectively control the material ingredients amount; in thermal power plant, coal quantity for the burner can be controlled accurately according to the load demand, which can realize the the optimal combustion conditions of burner. Using gas to convey pulverized solid materials such as coal, cement, salts, grains in the pipeline, can increase safety and reliability of the production, improve transport efficiency, avoid pollution of the environment, reduce costs[1]. But gas-solid two phase flow is different with single phase flow or gas-liquid two phase flow, it is more complex and changeable, many internal and external factors will directly affect its parameter measurement, such as temperature, humidity, solid phase particle size, material, etc.[2].

In order to realize the precise measurement of the gas-solid two phase flow parameters, the relational characteristics of gas-solid two phase flow have to be studied. The rate and flow of particles in gas-solid two phase flow are two greater influential parameters for describing powder flow, many of the gas-solid two phase flow research processes and actual production departments require for accurate measurement. Because now available on-line measurement system for industrial application is very few, it makes the related products of gas-solid two phase flow measurement have great market power. At present, many abroad manufacturers have produced the cross-correlation flow meter for solids rate and concentration

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Corresponding author: LIU Xiu (869830930@qq.com)

measurement, and it has applied to the industrial production. In our country, some research units also make the deeply studying in this aspect, the wind powder online monitoring system in the store type pulverizing boiler is developed by Tianjin institute of electric power test[3].

The flow measurement of gas-solid two phase flow is divided into two methods, i. e. direct measurement and indirect measurement method. Direct measurement method is to obtain the mass flow directly through the sensitive original of the sensors, the main methods are: hot research method, Coriolis flow meter, shock plate flow meter[4], differential method[5], etc. ; indirect measurement method is to obtain the mass flow indirectly by measuring the rate and concentration. Due to the direct measurement technique is immature and the measurement accuracy is low, so now the researches of two phase flow measurement technology focus on indirect measurement. Indirect measurement includes contact measurement and non-contact measurement. Any contact of contact sensor and pipeline may cause pipeline jam, and the abrasion can cause the frequent replacement of the sensor. In addition, the contact method will cause the pipeline pressure loss and energy loss[6]. So, now the focus of the research and development is the non-contact measuring instrument. This paper mainly introduces the non-contact particle rate and concentration measurement methods.

1 Rate measurement method

1.1 Doppler method

Doppler method uses Doppler frequency shift theorem as the basis of solid rate measurement. The energy from the waves into the fluid detected has a fixed frequency f_T, and the energy reflect to the receiver through the fluid particles with the frequency f_R. The signal frequency difference of transmit and receive has the relations with the rate of the fluid particles as

$$v_s = C\frac{f_R - f_T}{2\cos\theta f_T}, \tag{1}$$

where C is the rate of electromagnetic waves, θ is the angle between the transmission of energy to the fluid. C and θ are known, so solid rate can be measured by the Doppler frequency shift $f_R - f_T$. Based on the Doppler frequency shift theorem, laser, microwave or ultrasonic can be used as energy. Laser Doppler tachymeter can realize the particle rate point measurement in the pipe of gas-solid two phase flow in the range of 0.1 — 100 mm/s, with measuring accuracy reaching ±0.5% and no need calibration. Measurement result is not affected by conveying air temperature, and it can be applied to the study of science. However, its cost is too high, device is easy to damage, and it needs transparent glass installed in the industrial device to allow light to enter and receive, which limits its industrial applications.

Microwave as the energy rateometer comes in two forms, namely the transceiver division mode and single-base mode. Compared with laser Doppler velocimeter, it does not need the transparent window and has the simple and compact structure, so that it can be suitable for bad industrial environment, and the price is relatively cheap. Microwave is divergent. In the area of the test, due to different angles of different mobile rate of particles, signal frequency received is not a single frequency, but the superposition of multiple frequency signal results in low spatial resolution of measurement device, and it is difficult to achieve point rate measurement[7-8].

1.2 Correlation method

Correlation method is that using the internal flow noise of fluid or modulation of additional energy to produce random signal similarity to achieve rate measurement, without any external investment tracer. On the physical implementation, we just install two identical sensors with its axial distance of L in pneumatic conveying pipeline, and its principle diagram is shown in Fig. 1.

Correlation method is characterized by wide measuring range, strong adaptability. Simply select appropriate sensors, and main body of the related flow measurement system is constant. Make sensors as "clamp" type, which have no moving parts and don't hinder the flow. A large number of experiments show that the flow rate obtained by using this method is higher than actual average flow rate of parti-

cles[9-10].

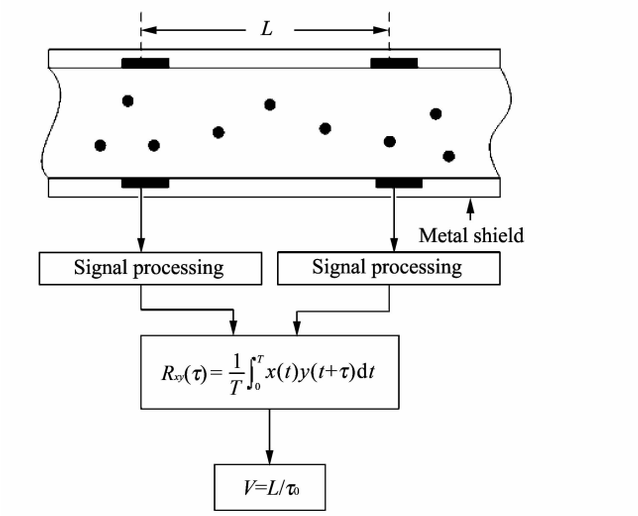

Fig. 1 Principle diagram of cross-correlation particle rate measurement

The method of rate measurement also has spatial filtering method and tracer method. Spatial filtering method as a kind of optical rate measuring method is put forward by Ator[11] in 1960s, which can realize particles and object movement rate measurement. Without higher spatial resolution, this method has the advantages of simple structure of measurement device, good stability of optical and mechanical properties, wide selection of light source and convenient data processing. The principle of tracer method is same as that of related rate measurement, but it need to join tracer in either of the two phase flow, and the flow rate of the mixture is determined according to the downstream tracer sampling or testing time. The principle of this method is simple and it need not groups but convenient installation of the device, but even if the radioactive source uses a short half-life of isotopes, it also can cause serious pollution and high cost[12].

2 Concentration measurement method

2.1 Attenuation method

On the whole, monochromatic electromagnetic waves or sound waves through the particulate medium all obey Lambert Beer's law as

$$I = I_0 e^{-\mu x}, \quad (2)$$

where I and I_0 are the initial incident and output intensity of electromagnetic wave or sound wave respectively, x is the effective thickness of wave through the medium, μ is a constant (linear attenuation coefficient). Based on the principle, by firing a beam or multi-beam electromagnetic or sound waves through pneumatic conveying pipes, the researchers have developed several kinds of techniques which uses attenuation caused by flow medium to detect the concentration of solid phase. The electromagnetic wave for concentration measurement can be visible light, laser, microwave, ray. In addition, measuring the attenuation produced by particle scattering can also realize the solid phase concentration detection.

These different "source" of sensors has its own characteristics. Ray method has wide measurement range, high space points rate, but the structure equipment is complex, expensive, and its improper application can be prone to radiation leakage. The main advantage of optical sensor[13] is that if all the particles measured are opaque, the change of chemical composition and humidity has no effect on the system output actually, but the change of the optical system is easily contaminated, which will generate large measurement error. As shown in Fig. 2, Zhu et al. designed a five fiber optical probe[14].

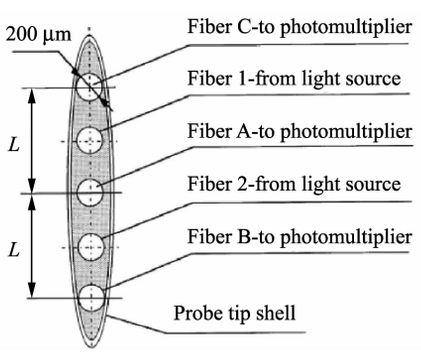

Fig. 2 Five fiber optical probe structure

For microwave sensor, field test shows that the attenuation along with the change of moisture and particle size has a significant change, and the particle deposition in the microwave window will cause the dramatic increase of attenuation which results in error. Acoustic method can estimate solid phase concentration roughly, which is suitable for detecting leaks and not suitable for absolute measurement of

solid phase concentration[14]. Therefore, for attenuation type phase concentration measurement method, choose the sensor according to different application.

2.2 Process Tomography method

Process Tomography method (PT) was formally formed in the mid 1980s and developed a kind of the process parameters on-line real-time detection technology which makes two phase flow as the main object. It uses the similar principle of medical computer tomography (CT) to measure the flow parameters of two phase flow, such as particle concentration or the distribution of two-dimension (2D) or three-dimension (3D) of volume fraction. According to the different sensing methods, PT technology includes capacitance method, charge induction method, ultrasonic method, ray method and others. Due to the PT can realize non-disturbed, multiple parameter 3D measurement on the flow field, it has a strong vitality in the two phase flow pattern identification and parameter measurement. The main difficulties of PT technology for online measurement are signal detection, image reconstruction and flow parameters obtaining. Two phase flow in general is a kind of unsteady flow and complex flow pattern distribution. In order to describe the local spatial distribution accurately as much as possible, it needs to use more sensors[15]. There are many factors influencing the sensitive volume change in two phase flow, and the relationship between the measure and the sensitive load is nonlinear, so researching and developing the reconstruction algorithm which is suitable for different occasions, is an important research direction of PT technology.

2.3 Resonance method

Under certain conditions, when the particulate matter gets the external energy, physical resonance phenomenon occurs. Based on resonance principle, nuclear magnetic resonance (NMR), microwave resonance and acoustic resonance phase concentration sensor have been developed. The basic principle of NMR is when put the net magnetic material in the proper frequency electromagnetic field, the nucleus can obtain energy from the field on the Lamor frequency, and make them happen resonance transition between magnetic energy levels. NMR method measuring the phase concentration has no relation with some parameters such as the conductivity of the fluid or temperature change, which belongs to the way of non-contact measurement. It is suitable for measuring the corrosive substance and polymerization with high precision, but it has complex structure, high cost and bad economical efficiency. Microwave resonance method is to use a length of pillar insulating materials covered with the metallic conduit to make up of the microwave cavity, through holes to connect the microwave system, and the energy can be absorbed in the cavity from microwave system at a specific resonance frequency. The frequency shift of the resonant frequency from the cavity is empty to have a solid substance and is proportional to the concentration of solid phase in the cavity, which can realize the concentration measurement of solid phase. The technology is extremely sensitive to solid phased particles moisture and temperature changes, therefore, extra precautions must be taken to make temperature stability and correct the change of moisture content. Acoustic resonance method is to use proper geometry shape sensor to produce acoustic resonance, the resonance frequency is directly proportional to the rate of sound, which is calculated by the acoustic resonance frequency measured, and then calculate the concentration of solid phase. Vetter and Culick[16] studied for the power plant coal conveying pipeline, confirmed that the acoustic resonance method can be used to obtain solids average concentration, but the system output is related to particle size and only sensitive to particles of size less than 100 μm.

2.4 Electrical method

Based on the dielectric properties and electrostatic properties of the moving particles, two kinds of simple, low cost of particle concentration measurement devices were developed, i. e. the capacitance method and static method. This paper mainly introduces the electrostatic method.

The basic principle of capacitance method is that in gas-solid two phase flow, dielectric constant of the solid phase material is generally bigger than gas,

therefore, in the sensitive space of capacitance, the existence of the solid-phase material will make capacitance value measured increase. The change of capacitance value can be converted to the appropriate electrical signals through a dedicated circuit. The corresponding relations between detection capacitance and the concentration of solid phase can be direct or indirect. The main advantage of the capacitance sensor is noninvasive measurement, non affecting the flow field, simple structure, good cost performance, easy to install, fast response rate, good real-time, wide applicable scope, etc.[17]. But in practice, there are many nonnegligible problems such as: the capacitance measured value and phase concentration is not a one-to-one correspondence linear relationship, and the relationship between the parameters is difficult to describe directly with analytical description; the measured value of the capacitance is vulnerable by the change of phase distribution and flow pattern, which leads to a larger measurement error, etc.

2.4.1 Measuring principle

Electrostatic method is a kind of electric method, which is based on electrostatic characteristics of flow powder particles to realize two phase flow parameters detection. During the pneumatic conveying process, because of the friction between particles and device wall, collision, and separation between particles, particles and pipeline will accumulate a large amount of electric charge. Detecting particles static noise occurring in the flow process or transfer of power between particles and test device with the appropriate signal processing method, can realize particles flow parameter measurement and real-time detection of particle size.

2.4.2 Principle of electrostatic sensor

In the pipeline, the load capacity on the mobile particles can be measured by a shield insulation probe combined with proper processing circuit. Measuring probe structure can be used in a circular ring or rod electrode, as shown in Fig. 3. Measurement circuit can be designed in communication detection circuit according to the requirements, namely measuring the communication components of electrostatic sensor output signal, or measuring all of electrostatic sensor output signal (DC method)[18]. A large amount of experimental studies show that communication method is superior to the DC method.

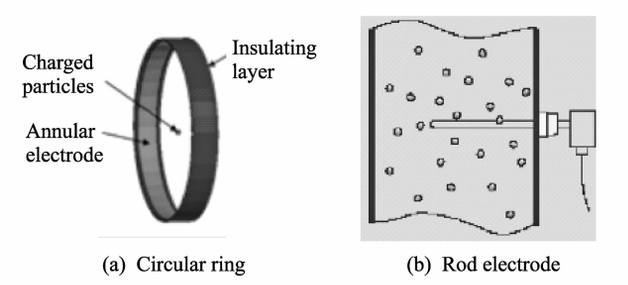

Fig. 3 Particle concentration detection electrode

Shield, metal electrodes and amplification circuit constitute the electrostatic sensor system. When the flow particles cause induced electric field fluctuations, electrostatic sensor measurement system can detect static random signal. The charged solid particles flowing through probe produce the space electric field, and the electric field produces induced charge on the metal electrodes. The quantity of induced charge changes with electric field change in the the probe induced area. Suppose the particle induced charge on the electrode is $q(t)$, the model of the output voltage $u(t)$ can be represented by the circuit shown in Fig. 4.

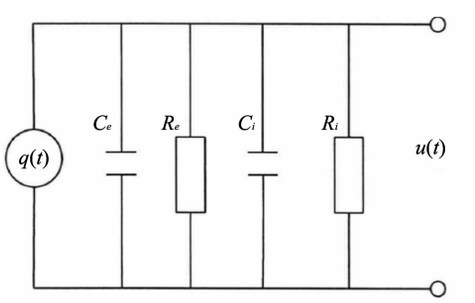

Fig. 4 Electrostatic sensors equivalent circuit

R_e and C_e are sensor probe equivalent resistance and equivalent capacitance; R_i and C_i are the equivalent input resistance and input capacitance of preamp. According to the Kirchhoff's current law,

$$\frac{\mathrm{d}q(t)}{\mathrm{d}t} = C\frac{\mathrm{d}u(t)}{\mathrm{d}t} + \frac{u(t)}{R}, \tag{3}$$

where

$$R = \frac{R_e R_i}{R_e + R_i},\ C = C_e + C_i.$$

By the Laplace transform,

$$\frac{U(s)}{Q(s)} = \frac{sR}{1+sRC}. \tag{4}$$

When $|sRC| \ll 1$, the measurement model of induction charge can be obtained as follows

$$u(t) = R \cdot q(t). \tag{5}$$

From the type it can be seen: electrostatic sensor output voltage and induced charge on the electrode has a linear relationship, so in the design of detection circuit, a voltage detection circuit can be used[19-20].

2.4.3 Electrostatic sensor research progress and application

In 1995, by using non-contact circular electrostatic sensor and cross-correlation principle, Yan et al. measured and obtained the solid phase rate with rate range of 2 — 40 m/s and repeatability error within ±2%[21]. In 1996, Gajewski[22] used annular electrostatic sensor and the principle of mean square error to measure and obtain solid mass flow rate. In 2000, Coulthard[23] used annular electrostatic sensor and indirect measurement method of the mass flow rate and obtained the parameters of solid mass flow rate. In allusion to dilute phase flow, used three electrodes to complete the solid mass flow rate parameter measurement, and the measurement result is not affected by flow pattern. In 2002 and 2003, Armour and Woodhead[24] using annular electrostatic sensor experiment discussed the fluid rate, particle size, particle material, air relative humidity and temperature on the influence of charged particles. In 2003, Zhang[25] used a new type grid electrostatic sensor measuring the solid particle size, the measurement error ranged within ±15%. In 2005, using rod sensing electrode and the principle of cross-correlation, Yan[3] completed the solid rate measurement. In 2008, Xu[26] using annular electrostatic sensor and random electrostatic signal peak frequency realized the spatial filtering method measuring solid phase rate.

In 2001, the British trade pointed out in the technical report of "Power plant boiler pulverized coal flow measurement and control methods": In the past few years, about the pulverized coal flow rate, concentration or the mass flow rate, there have developed a number of methods. Among them, the most promising methods (i.e. achieve the status of the application) is static, microwave and acoustic technology[27]. At present, ABB company (PFMaster, the annular electrode with different width)[2], TR - Tech company (three apart 120° insert electrodes), PCME company (50 mm apart insert electrode), ESKOM company (6 parallel insert electrode)and other manufacturers abroad have produced the flowmeter on the basis of the principle of electrostatic and has been applied to the industrial environment, as shown in Fig. 5. Although the electrostatic sensor model has been applied in the study of the gas-solid two phase flow parameters detection test, but in the process of establishing dynamic mechanism model, there are a lot of assumptions, that the characteristics of spatial filtering and frequency band are mostly qualitative, at the same time there are still many questionable in the results and analysis.

Fig. 5 ABB PFMaster flowmeter

3 Conclusion

Measuring methods described above of the rate and concentration of gas-solid two phase flow have their own advantages and disadvantages and applicable occasions. However, measuring instruments based on the different mechanism in the particles flow parameter measurement of the gas solid two phase flow play the various roles. But, with the deepening research on two phase flow and growing requirements of accurate measurement, non-contact measurement of online particle rate and concentration is imperative. In these methods, static sensing technology because of its simple structure, low cost, high sensitivity, become the most development and application prospects method in the gas-solid two phase flow parameters detection.

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气固两相流速度-浓度检测技术的研究分析

刘 秀[1], 刘 吉[1,2], 张 静[1], 颜 兵[2], 史璐璐[1]

(1. 中北大学 电子测试技术重点实验室, 山西 太原 030051;
2. 中北大学 信息与通信工程学院, 山西 太原 030051)

摘 要: 对气固两相流速度和浓度的间接检测方法、基本原理、应用范围及研究成果进行了论述。分析和总结了速度、浓度检测技术的发展现状和存在的问题。着重分析了浓度测量中静电法测量相浓度技术在工业应用中存在的问题及研究现状。给出了静电式相浓度传感器的设计准则, 阐明了该传感器用于相浓度测量的优越性及其广阔的工业应用前景。

关键词: 气固两相流; 速度-浓度; 静电法

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