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# Study on the measurement of paste flow based on the optical fiber system

**Abstract**

Purpose - Flow measurement plays an important role in modern industrial production. Flow measurement methods based on optical fiber systems have become a main research focus.

Design/methodology/approach – Applying flow measurement theory and the structural characteristics of optical fiber, flow measurement of paste can be achieved through a combined laser Doppler and optical fiber sensing system based on the principle of optical fiber grating sensors and flow sensors. The system is developed to include light selection, photoelectric detection, a voltage amplifier circuit, and a signal filtering circuit.

Findings – The system is shown, through a comparative experiment, to be of higher accuracy than the traditional ultrasonic method.

Originality/value – A new method for measuring the paste flow is presented, which is based on the principle of optical fiber Doppler. The method has the advantages of convenient installation, high accuracy and low cost. Experiments show that the method is feasible.

**Keywords** Optical fiber technology, Flow measurement, Paste, Laser Doppler

**Paper type** Research paper

## 1. Introduction

The main methods available for measuring slurry flow are: (1) the differential pressure method; (2) the electromagnetic method; (3) the Doppler ultrasonic method; (4) the volume method; and (5) the Coriolis mass method.

A differential pressure flow meter (1) can be used for measuring the flow rate of various slurry fluids. The Venturi tube is generally used to ensure that the throttle device does not deposit solid particles. It is important to take care to avoid abrasion and issues with paste material jamming. The electromagnetic method (2) can measure pulp, coal slurry, slurry and other high-conductivity liquids, but this sensor cannot be installed in a horizontal pipe. The Doppler ultrasonic method (3) may introduce large measurement errors because of the heavier flow on the bottom of the tube. The volume method (4) is the most traditional measurement approach, but its efficiency is considered to be too low. The Coriolis mass method (5) can be used to measure the flow of liquid containing a small amount of solid particles; however, when the quantity of solids increases, and the solid particles are large, then the issue of anti-blocking must be considered(Wang and Zhang, 2014; Wang *et al.*, 2015; Binzoni and Martelli, 2015; Andrzej *et al.*, 2015; Tajima *et al.*, 2014).

Paste filling is an important method for mine filling, and flow measurement is, therefore, the first problem to be solved. Optical fiber sensing technology is introduced into the flow measurement to provide improved accuracy and stability. Optical properties such as intensity, phase, and frequency of the light transmitted in the optical fiber are controlled, and appropriate optical detection methods can then convert it into electrical signals. The resulting flow measurement instrument is highly complex and both the flow meter measurement principles and the measurement method have their advantages and disadvantages. Optical fiber Doppler sensors have rapidly developed in recent years to measure flow with high precision, fast dynamic response, good space differentiating ability as well as many other advantages. Consequently, it is becoming one of the main methods of flow measurement. Based on the scattering principle, the laser Doppler and the optical mixing principle, an optical fiber Doppler sensing system is designed, including the optical detection circuit, voltage amplification circuit and low-frequency filtering circuit.

## 2. Optical fiber Doppler sensing principle

The principle behind an optical fiber Doppler flow sensor is based on the scattering of light by paste particles and the optical fiber Doppler principle, whereby the frequency of the light is modulated by the flow. The optical signal is then converted to an electrical signal by a photoelectric detector, and the frequency information is obtained by voltage amplification and a low-frequency filtering circuit.

### 2.1 Scattering principle

When the particle's diameter $D << \lambda$, usually $D / \lambda < 0.1$, then it belongs to Rayleigh scattering. When $D \sim \lambda$, or $D < \lambda$, then it belongs to Mie scattering. When $D > \lambda$, then it belongs to Anomalous diffraction. When $D >> \lambda$, usually $D / \lambda > 10$, it belongs to Fraunhofer diffraction.

### 2.2 Optical fiber Doppler principle

When there is relative motion between the wave source and the observer, then the wavelength of the radiation will change. Light is a special kind of wave that exhibits the Doppler effect with a change in frequency.

When the light is static, and the observer has relative motion, then the observed frequency is:

$$f_1 = \frac{c \pm v}{c} f_0 \tag{1}$$

where:
$f_0$ is the frequency of the light source;
$v$ is the relative speed between the light and the observer; and
$c$ is the speed of light in a vacuum.

When the observer is static, the light has relative motion, and the observed frequency is:

$$f_1 = \frac{c}{c \pm v} f_0 \tag{2}$$

The light meets the paste particles—exhibiting relative motion—and the first frequency shift occurs. At the same time, each paste becomes a scattering center and the light is scattered by the paste particles. The detector receives the second frequency shift of scattered light. The Doppler frequency shift due to the paste, of flow rate *v,* is given by(Chen *et al.*, 2015; Masayuki *et al.*, 2012; Zhu *et al.*, 2012):

$$\Delta f = f_2 - f_0 = f_0 \frac{vn}{c}\left(\cos\theta_1 + \cos\theta_2\right)$$

$$= \frac{vn}{\lambda_0}\left(\cos\theta_1 + \cos\theta_2\right) \quad (3)$$

The flow rate, $v$, is given by:

$$v = \frac{\Delta f \lambda_0}{n\left(\cos\theta_1 + \cos\theta_2\right)} \quad (4)$$

The flow $Q$ is equal to:

$$Q = \frac{v\pi D^2}{4} = \frac{\pi\Delta f \lambda_0 D^2}{4n\left(\cos\theta_1 + \cos\theta_2\right)} \quad (5)$$

## 2.3 Optical mixing principle

Optical mixing technology is a coherent detection technology. An optical fiber Doppler flow sensor mixes the original signal and the frequency-shifting signal to achieve flow measurement. The wave equation of $e_0$ and $e_1$ is given by:

$$e_0 = E_0 \cos\left(\omega_0 t + \varphi_0\right) \quad (6)$$

$$e_1 = E_1 \cos\left(\omega_1 t + \varphi_1\right) \quad (7)$$
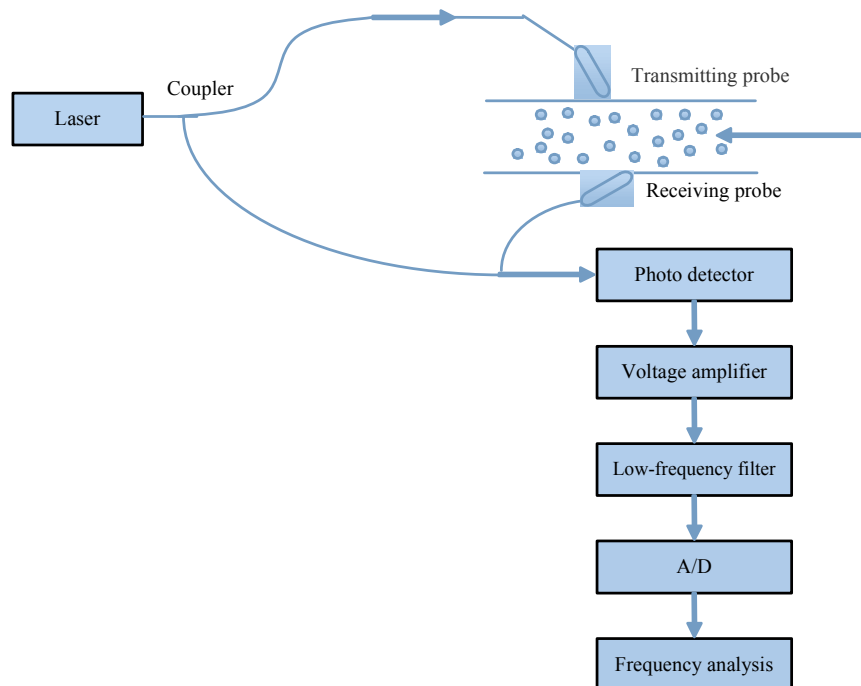
where:

$E_0$ and $E_1$ are the amplitudes of the light;

$\omega_0$ and $\omega_1$ are the angular frequencies of the light; and

$\varphi_0$ and $\varphi_1$ are the initial phase angles of the light.

The two beams are incident upon the photoelectric detector; the resulting wave equation is:

$$e = E_0 \cos\left(\omega_0 t + \varphi_0\right) + E_1 \cos\left(\omega_1 t + \varphi_1\right) \quad (8)$$

The photoelectric detector is only sensitive to the light intensity, which is the square of the amplitude of the wave.

$$
\begin{aligned}
E^2 &= \left[E_0 \cos(\omega_0 t + \varphi_0) + E_1 \cos(\omega_1 t + \varphi_1)\right]^2 \\
&= E_0^2 \cos^2(\omega_0 t + \varphi_0) + E_1^2 \cos^2(\omega_1 t + \varphi_1) \\
&\quad + E_0 E_1 \cos[(\omega_0 + \omega_1)t + (\varphi_0 + \varphi_1)] \quad (9) \\
&\quad + E_0 E_1 \cos[(\omega_1 - \omega_0)t + (\varphi_1 - \varphi_0)]
\end{aligned}
$$

The photoelectric detector is a high-frequency cutoff device, which cannot directly respond to the optical frequency. The output is only the average value of the first three terms.

$$E^2 = \frac{E_0^2 + E_1^2}{2} + E_0 E_1 \cos[(\omega_1 - \omega_0)t + (\varphi_1 - \varphi_0)] \quad (10)$$

The Doppler shift is given by:

$$\Delta f = \frac{\omega_1 - \omega_0}{2\pi}$$

The signal frequency detected by the photoelectric detector is the Doppler shift. In this way, the speed of the paste can be obtained by the frequency analysis(Mohd et al., 2012; Mayo et al., 2012).

## 3. The design of the optical fiber Doppler sensing system

The optical fiber Doppler sensing system is shown in Figure 1.

Figure 1 The optical fiber Doppler sensing system

The laser is sent into the transmitting probe through the coupler before then being scattered into the receiving probe. The signal is sent to the photo detector, voltage amplifier, low-frequency filter, and the A/D converter before being finally converted to the frequency.

## 3.1 Photoelectric detection circuit

The photoelectric detection element in the circuit is a PIN photodiode, which has the characteristics of fast reaction speed, good sensitivity, and a small current with no light. The signal strength of an optical fiber Doppler flow sensor is very weak. The specific photoelectric detection circuit is shown in Figure 2, where R1 is a load resistor; and an RC filter circuit comprises R1 and a filtering capacitor C12.

Figure 2 Photoelectric detection circuit



The photocurrent of the photodiode is $I_p$, and the output voltage of the integrating operational amplifier is given by:

$$U_0 = I_p R_1 \tag{11}$$

If the responsivity of the photodiode is $R$, and the light power is $P$, then the light current is given by:

$$I_p = RP \tag{12}$$

$$U_0 = I_p R_1 = RPR_1 \tag{13}$$

The output voltage is, therefore, linear with the light power.

## 3.2 Voltage amplifier circuit

A differential voltage amplifier circuit is shown in Figure 3. The amplifying circuit has two levels. The first-level amplifying circuit comprises operational amplifiers U2A and U3A, feedback resistors R7, R8 and R4; the second level amplifying circuit comprises operational amplifier U4A, which is a proportional inverse amplifying circuit. The peripheral circuit is a symmetric structure applying a high-precision resistor R4 in order to adjust the circuit's magnification. The symmetrical structure of the differential voltage amplifier circuit can suppress the zero drift, noise and offset voltage—greatly improving the measurement accuracy of the circuit.
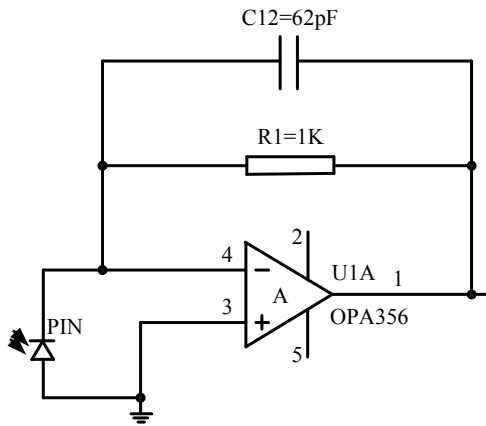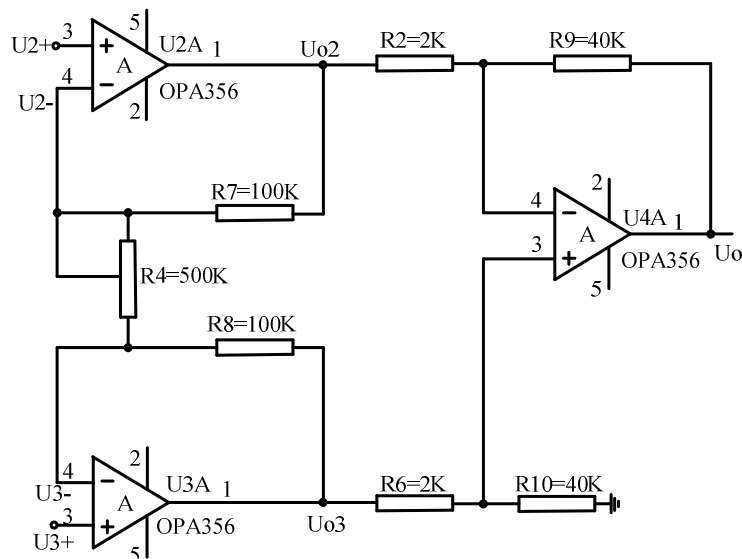
Figure 3 Differential voltage amplifier circuit



The operational amplifier is an ideal amplifier, and the input current is 0. The output voltage of U2A and U3A are:

$$u_{02} = \left(1 + \frac{R_7}{R_4}\right) \cdot u_{2+} - \frac{R_7}{R_4} u_{3-} \tag{14}$$

$$u_{03} = \left(1 + \frac{R_8}{R_4}\right) \cdot u_{3+} - \frac{R_8}{R_4} u_{2-} \tag{15}$$

$$u_{2+} = u_{2-} \tag{16}$$

$$u_{3+} = u_{3-} \tag{17}$$

Substituting into (14) and (15) to give:

$$u_{02} = u_{2+} + \frac{R_7}{R_4}\left(u_{2+} - u_{3+}\right) \tag{18}$$

$$u_{03} = u_{3+} - \frac{R_8}{R_4}\left(u_{2+} - u_{3+}\right) \tag{19}$$

When $R_7 = R_8$, the output voltage of U4A is given by:

$$u_0 = \left(1 + \frac{R_9}{R_5}\right) \cdot u_{02} - \frac{R_9}{R_5} u_{03} \qquad (20)$$

By substituting (18) and (19) into (20), we can arrive at:

$$u_0 = (u_{2+} - u_{3+}) \cdot \left(1 + \frac{2R_7}{R_4}\right) \cdot \frac{R_9}{R_5} \qquad (21)$$

Since $u_i = u_{2+} - u_{3+}$, then:

$$u_0 = u_i \cdot \left(1 + \frac{2R_7}{R_4}\right) \cdot \frac{R_9}{R_5} \qquad (22)$$

### 3.3 Filtering circuit

The frequency-shift signal of the optical fiber Doppler flow sensor varies from 0 to 2.5 MHz, so the low-pass filter is used to filter all high-frequency signals, as shown in Figure 4. The transfer function of the circuit is:

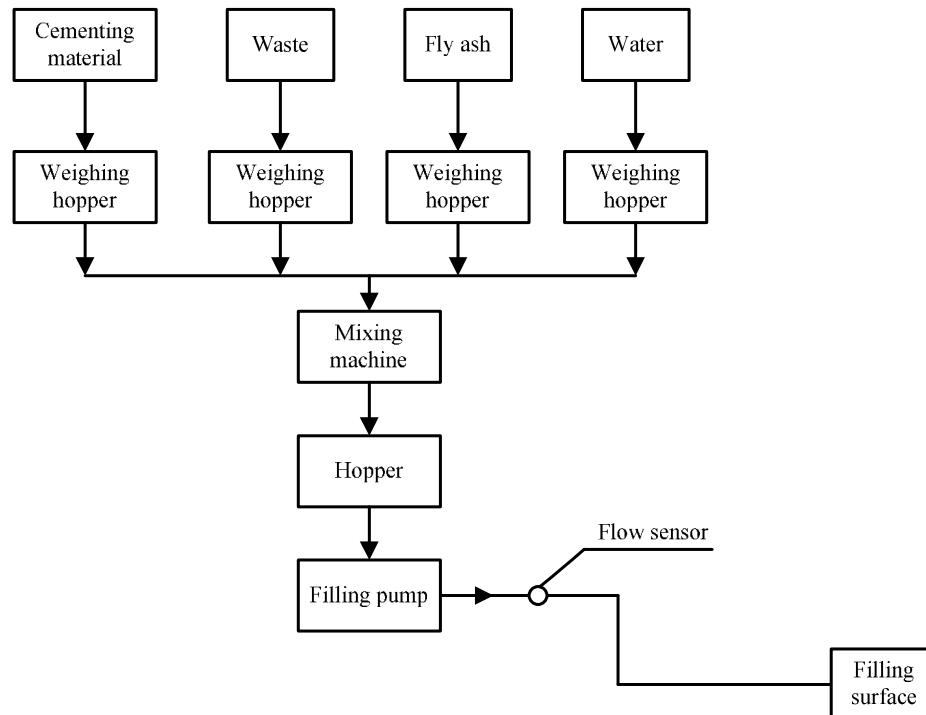$$G(s) = \frac{U_0(s)}{U_i(s)} = -\frac{R_{12}}{R_2} \cdot \frac{1}{1 + R_{12}C_{11}s}$$

$$= -\frac{R_{12}}{R_2} \cdot \frac{\omega_c}{s + \omega_c} = K \frac{\omega_c}{s + \omega_c} \qquad (23)$$

The pass-band gain of the circuit is given by $K = -\dfrac{R_{12}}{R_2}$, the cutoff angular frequency $\omega_c = 1/(C_{11}s)$, $R_2 = R_{11} = R_{12} = 20K\Omega$, $C_{11} = 3.15\,pF$.

In order to reduce spurious coupling of each part of the amplifier circuit through the common DC power, the circuit not only has $\pm 2.5$ Vdc power, but can also effectively prevent oscillation and interference. In addition, in order to prevent self-oscillation of the circuit, the positive and negative power rails of the amplifiers are connected in parallel to an anti-coupling capacitor.

Figure 4 Low-pass filter



## 4. Experiments

The paste flow measuring equipment for the experiment is a coal mine filling pump and conveying pipeline. The whole set of equipment comprises two parts: the conveying system and the measuring system. The conveying system includes an HBT90 paste slurry pump, a 2 m$^3$ mixer, a weighing meter, and a pipeline of 219 mm diameter and length of 1800 m (including pipe elbow and valve). The measuring system, shown in Figure 5, includes both an ultrasonic and an optical fiber Doppler flow meter.
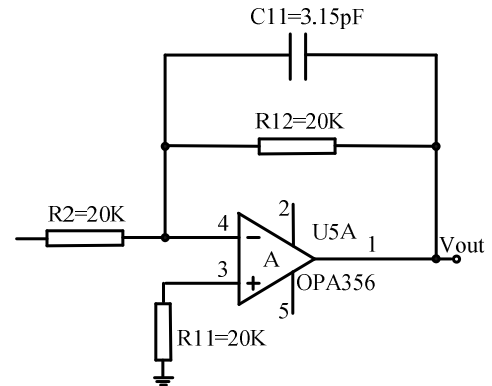
Figure 5 The measuring system



When varying the coal mine filling materials, different kinds of fly ashes lead to different quality concentrations of the filling material, which varies between 72% and 81% with different filling slurry materials at each volume. The corresponding range of filling raw material per cubic meter is presented in Table 1.

The measurement data and the accuracy of the two methods (ultrasonic and optical fiber Doppler) are compared by applying the weighing method of real flow, which is shown in Table 1. The results show that the laser Doppler optical fiber system has higher accuracy. In particular, the error is relatively small for small flows.

Table 1 The comparative experiment

| Real flow($m^3$/h) | 316.67 | 339.29 | 361.91 | 384.53 | 407.15 | 429.77 | 452.39 |
|---|---|---|---|---|---|---|---|
| Flow of ultrasonic($m^3$/h) | 298.77 | 325.24 | 349.01 | 372.55 | 395.34 | 419.66 | 444.69 |
| Errors (%) | 5.65 | 4.14 | 3.56 | 3.12 | 2.90 | 2.35 | 1.70 |
| Flow of optical fiber Doppler ($m^3$/h) | 313.12 | 335.56 | 358.51 | 381.36 | 403.87 | 426.55 | 449.46 |
| Errors (%) | 1.12 | 1.10 | 0.94 | 0.82 | 0.80 | 0.75 | 0.65 |

## 5. Conclusions

In this paper, a new method for measuring the paste flow is presented, which is based on the principle of optical fiber Doppler. The system has the characteristic: photoelectric detection element in the circuit with fast reaction speed, good sensitivity and a small current without light; symmetrical structure of the differential voltage amplifier circuit with zero drift, noise and offset voltage; low-pass filter with effectively preventing oscillation and interference. The method has the advantages of convenient installation, high accuracy and low cost. Experiments show that the method is feasible.

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Mayo M., Hizuru N. and Akihide H. (2012), "Low-cost optical detectors and flow systems for protein determination", *Talanta*, Vol.96 No.0: pp. 121-126.
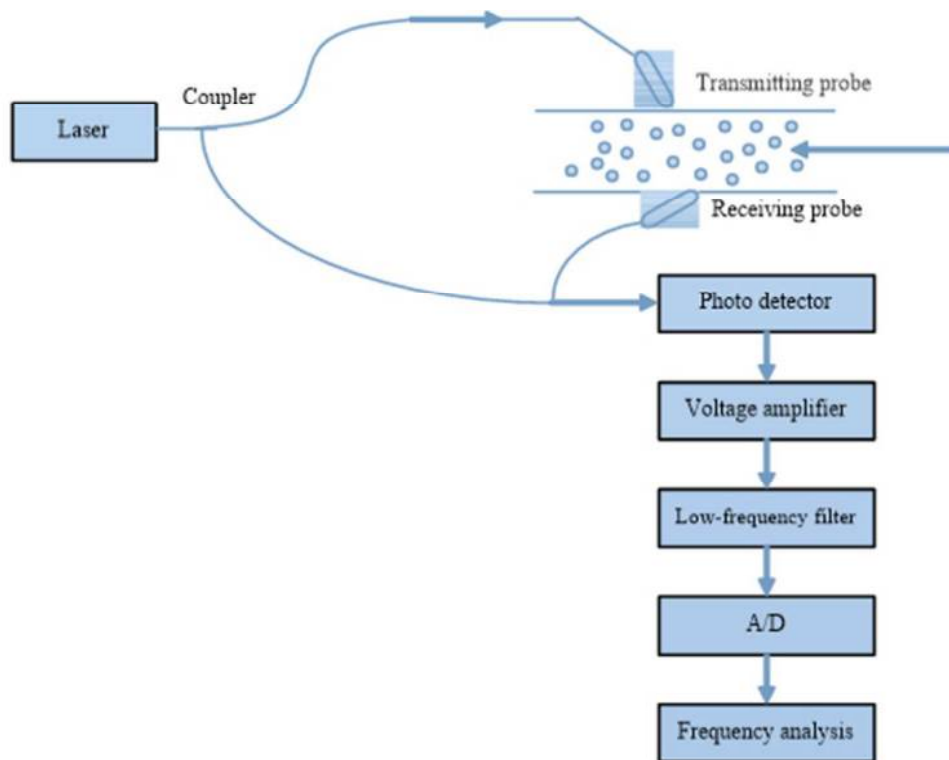
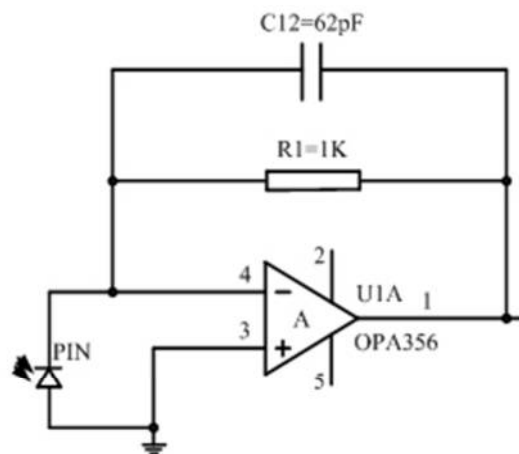Figure 1 The optical fiber Doppler sensing system
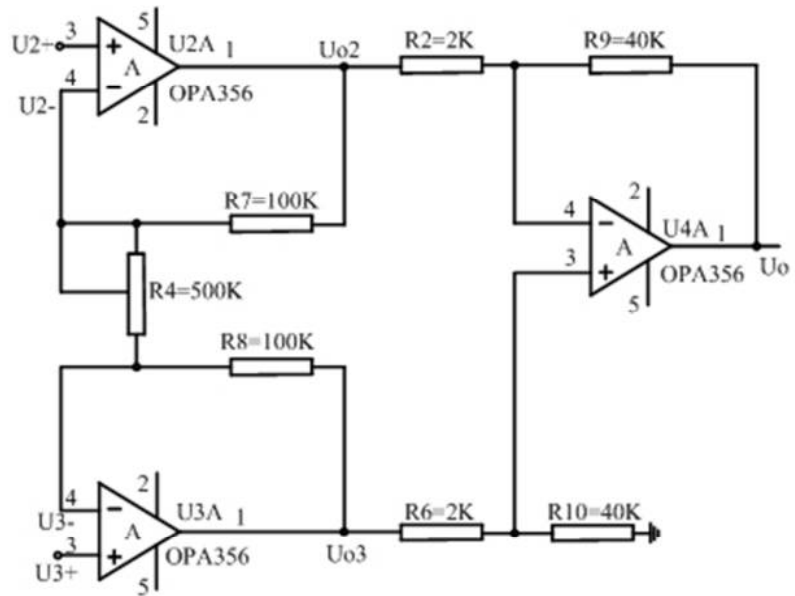
Figure 2 Photoelectric detection circuit
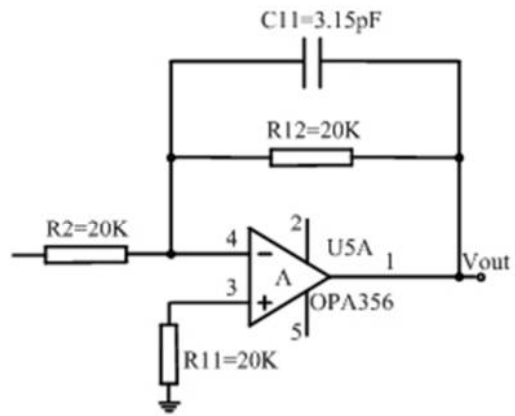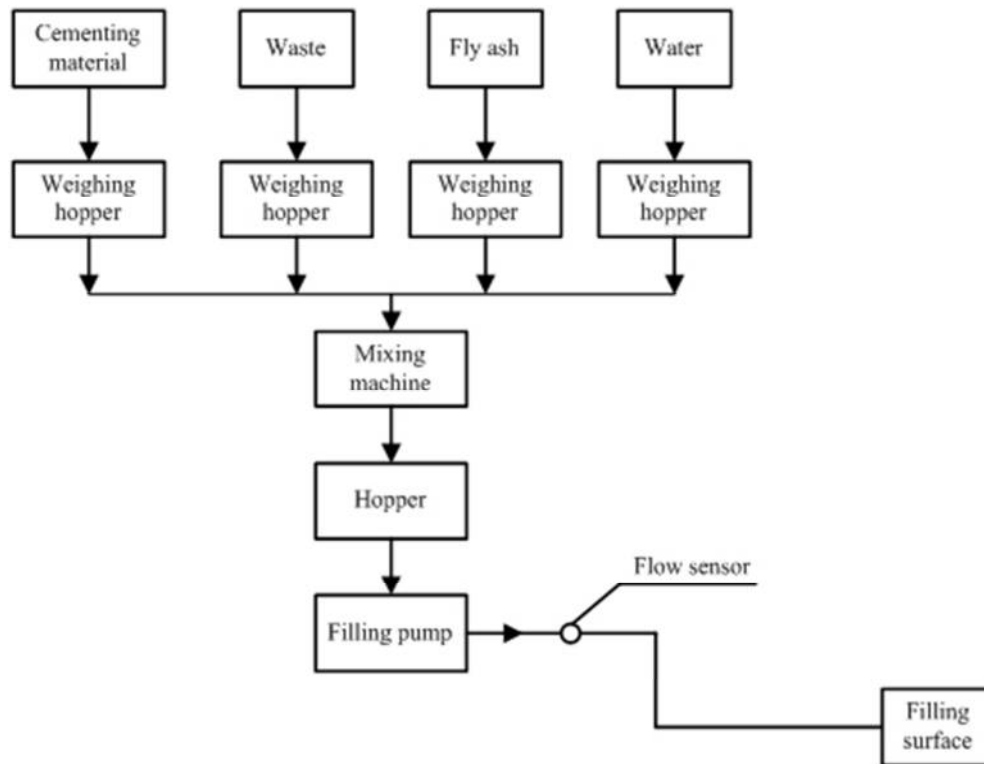
Figure 3 Differential voltage amplifier circuit

Figure 4 Low-pass filter

Fig.5. The measuring system