# Optimal Flow Characteristics and Timing Error of Rotary Flow diverters

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**Abstract**

The function expression of the flow characteristics of rotary flow diverters was deduced. It can be seen from the expression that when the splitter plate of the diverter moves at a constant speed through the nozzle slot, the optimal flow characteristic curve with an approximately linear relationship is obtained. A flaw of the "Biryukov curves" was pointed out. It is also proposed that the essence of the flow diverter timing error $\Delta t$ is the error caused by the installation asymmetry and the flow characteristic asymmetry, not the travel difference. The tow computational equations of timing error were deduced, the equation in JJG164-2000(flowmeter method) and the one in ISO4185 standard (static weighing method). A stepper motor drive system was designed, and experiments on the installation asymmetry of the diverter were carried out. The experimental results show that when the diverter splitter plate is triggered in advance, the timing error produces a negative deviation while lag trigger produces a positive deviation; and the greater the distance from the center point, the greater the absolute value of the timing error.

## 1. Introduction

The flow diverter system is a key component used to obtain the standard liquid mass (or volume) during a period of measuring time for liquid flow calibration facilities with static method. Structurally, there are several structures such as herringbone type with single wing, vertical translation and horizontal rotating with double wing [1]. For example, National Metrology Institute of Japan (NMIJ) used the vertical translational diverter with double wing, which moves at a constant speed on the oil flow standard facility (3~300m$^3$/h)[2]. At present, herringbone rotary type flow diverters with single wing are widely used in the word.

Biryukov pointed out that the motion law $S_1(t)$、$S_2(t)$ of the movable parts of diverters determine the flow function for the transition section of diverters, and gave the curves of $Q_1$ $(t)$ and $Q_2$ $(t)$. However, Biryukov did not give the specific functional form of curves. Physikalisch-Technische Bundesanstalt (PTB) discussed a flow diverter moving at constant linear speed, the characteristics and principle of the flow diverter working process were analyzed[4]. However the mathematical model of the flow characteristics was not discussed. A photoelectric switch which can fine tune the position to correct the timing error was installed on a liquid flow standard facility of PTB[5]. Bingxin Cai et al., developed rotated flow diverters with a single wing driven by a servomotor. By controlling the movement of the servomotor, it is ensured that the diverter moves at a constant speed when the wing passing through the nozzle[6]. However, the author did not discuss the timing error when the diverter deviated from the symmetrical point. Zhu Lei and others also discussed the rotary flow diverter and gave the dynamic characteristic curves of the diverter [7], but did not explain the driving method of the diverter. Carlo Marinara, et al. (INRiM, Italy) optimized and designed a diverter structure. The author used an AC motor to drive the diverter, and recorded the moving process of the diverter with high-speed photography technology[8]. However, the authors did not discuss the driving function. Although the flow characteristics were symmetrical, there were still nonlinear segments in the flow characteristic curves. All-Russia Research Institute of Flow Metering used Particle Image Velocimetry (PIV) optical method in order to investigate the local characteristics of the liquid flow in the nozzle exit section of diverters and the uncertainty of turbulence on the flow measurement[9][10]. The formula of diverter's timing error of ISO4185 was deduced in reference [11], but the author did not explain the mechanism of the timing error. There was a flaw in the description of the relationship between the mass error and the timing error in the paper.

The flow characteristic curves $Q_{1,2}$ $(t)$ of the flow diverter passing through the nozzle is related to the driving method of the diverter, that is, it depends on the motion laws $S_{1,2}$ $(t)$ of the movable parts of the diverter. In the present paper, the motion functions $S_{1,2}$ $(t)$ of rotary type flow diverters are discussed, and the functions $Q_{1,2}$ $(t)$ of the corresponding flow characteristic curves of the diverter are given. The functions of Birukov curves are deduced. A flaw of the Biryukov curves is pointed out. It is also proposed that the essence of the flow diverter timing error Δt is the error caused by the installation asymmetry and the flow characteristic asymmetry, not the travel difference of the diverter. The two computational equations of the timing error are deduced, including the equation in JJG164-2000 (flowmeter method) and the one in ISO4185 standard (static weighing method).

## 2. Mathematical model of motion and flow characteristics

*2.1 Mathematical model of real flow characteristics*

Assuming that the motion functions of the cylinder driving the flow diverter to move in (to the weighting tank) and out (to the bypass) are $S_1$ (*t*) and $S_2$ (*t*) respectively, and the exit velocity of the nozzle is constant, that is, *V*= const., the motion track of the splitter plate (wing) of the diverter is shown in figure 1.

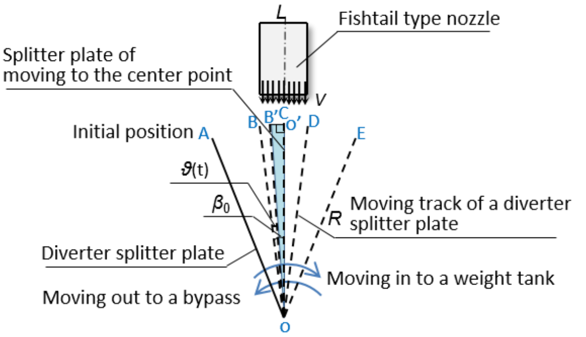


**Figure 1:** The trajectory of the diverter splitter plate

The initial position of the splitter plate of the diverter is OA, as shown in figure1. When moving in, the splitter plate passes through the position OA-OB-OC-OD-OE, and in reverses order when moving out. Among them, OB and OD are the positions where the tip of the plate just passes through the edge of the nozzle exit slot. Let us examine the right triangle △B'OO' while the splitter plate is in the OB position (any position of the nozzle). We can get the mathematical functions of the real flow character-ristics in the transition section of the diverter.

$$Q_{1,2}(t)=\left[\frac{L}{2}\pm R\sin\left(\left|\vartheta(t)\right|-\beta_0\times\frac{\pi}{180}\right)\right]bV \qquad (1)$$

$$\vartheta(t)=\int_0^t S_{1,2}(t)\mathrm{d}t$$

Where, $Q_{1,2}(t)$ are the flowrate to the weighing tank or standard container when moving in and moving out of the diverter. *L* is the nozzle width]. *b* is the nozzle length. *R* is the diverter wing rotation radius . $\beta_0$ is the 1/2 angle of the diverter wing passing through the nozzle slot, that is ∠BOC or ∠DOC in figure1. $\vartheta$ (*t*) is the rotation angle with OB (when moving in) or OD (when moving out) as the starting 0 °. 0 ≦ | $\vartheta$ | ≦ $2\beta_0$, $S_{1,2}(t)$ depends on the driving method to the movable parts of the diverter.

*2.2 Biryukov curves*

$Q_1$ (*t*) and $Q_2$ (*t*) are both determined by the motion functions $S_1$ (*t*) and $S_2$ (*t*) of the movable parts of the diverter [3]. The piston in the cylinder moves rapidly from one side to the other due to the action of air pressure, when the electromagnetic valve is switched, so as to drive the wing of the diverter to move left and right. From the flow characteristic curves of Biryukov, it can be confirmed that the Biryukov cylinder moves with a constant acceleration.

Assuming that the accelerations of move in and move out of the diverter are ± a0, then the mathematical models of driving functions $S_1$ (*t*) and $S_2$ (*t*) assumed by Biryukov are

$$S_{1,2}(t)=\omega(t)=\pm a_0 t \qquad (2)$$

Substituting Eq. (2) into Eq. (1), we can get Biryukov flow characteristic functions as below

$$Q_{1,2}(t)=\left[\frac{L}{2}\pm R\sin\left(\frac{1}{2}a_0t^2-\beta_0\times\frac{\pi}{180}\right)\right]bV \qquad (3)$$

The Biryukov motion and flow characteristic curves described by Eq. (2) and (3) are shown in figure 2.

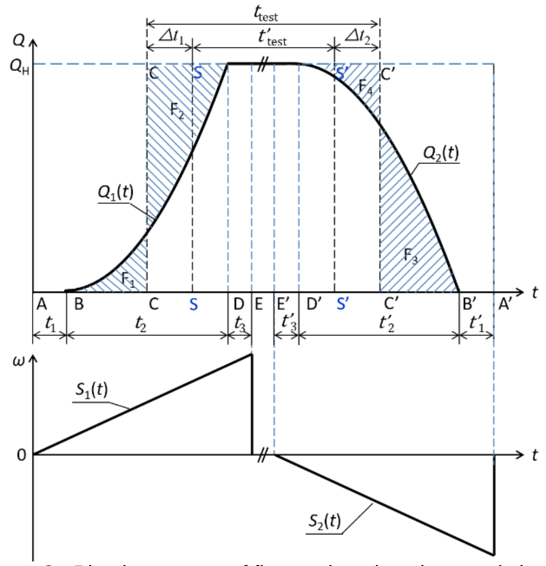


**Figure 2:** Biryukov curves of flow and motion characteristics

The Biliukov curves are obtained by assuming that the diverter moves with a constant acceleration, as analyzed above. However, when the cylinder makes reciprocating movement (the diverter moves in and out), it must experience the process from acceleration to deceleration and stop, rather than a single acceleration motion. Therefore, the actual diverter flow characteristic curves in figure 2 will not occurre.

*2.3 Optimal driving function and flow characteristics*
The actual motion law of diverters cannot be completely symmetrical, including the process of acceleration and deceleration during a single movement because of the instability of gas pressure and the randomness of resistance in the process of a piston movement. Therefore, in order to obtain the best flow characteristics, it is the ideal method by using a stepping motor to drive the diverter. Through software control design, the splitter plate of the diverter moves at a constant speed when passing through the nozzle slot, and makes the travel time equal when moving in and out.

The optimal mathematical models of the motion of rotary type flow diverters are

$$\omega(t)=\begin{cases} S_1(t)=\begin{cases} a_1 t & t_A \le t \le t_B \\ \omega_m & t_B < t \le t_D \\ \omega_m - a_1' t & t_D < t \le t_E \end{cases} \\ 0 \qquad\qquad\qquad\qquad\qquad t_E < t \le t_{E'} \\ S_2(t)=\begin{cases} -a_2 t & t_{E'} < t \le t_{D'} \\ -\omega_m & t_{D'} < t \le t_{B'} \\ -(\omega_m - a_2' t) & t_{B'} < t \le t_{A'} \end{cases} \end{cases} \qquad (4)$$

where, $a_1$、$a_1'$ are the acceleration and deceleration during moving in (to the weighting tank)；$a_2$、$a_2'$ are the acceleration and deceleration during moving out (to the bypass). $\omega_m$=const. It means that the splitter plate rotates at a constant rotational angular speed when passing through the nozzle slot.

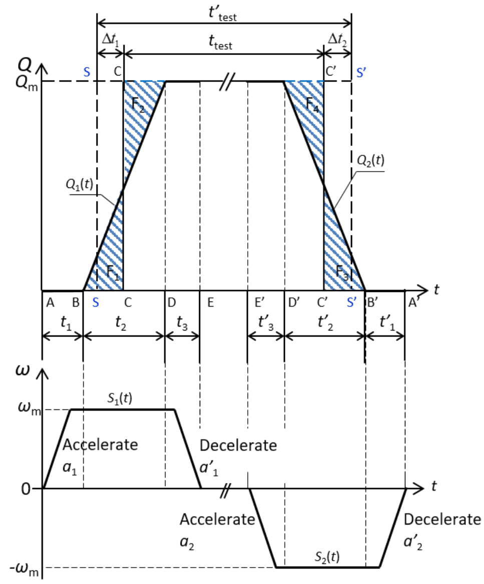


**Figure 3:** Optimal flow and motion characteristics of rotary diverters.

Substituting Eq. (4) $S_{1,2}(t)$ $=\pm\omega_m$ into Eq. (1) to obtain the optimal flow characteristic functions of the diverter:

$$Q_{1,2}(t)=\left[\frac{L}{2}\pm R\sin(\omega_m t-\beta_0\times\frac{\pi}{180})\right]bV \qquad (5)$$

The optimal flow characteristic curves and the optimal motion curves are shown in figure 3. It can be seen from the figure that the flow characteristic functions $Q_{1,2}$ ($t$) is approximately linear curves.

## 3. Timing error

The diverter system is a key component in achieving a high-accuracy liquid flowrate standard and guarantee of unified and magnitude transfer for liquid flow calibration facilities. At present, a photoelectric switch is mostly used to generate signals, which triggers the timing device, the reference flowmeters and the tested flowmeter(s) synchronously.

*3.1 The essence of the timing error*
The timing error of diverters $\Delta t$ means the timing error (also referred to as "timing correction" in the present paper) when the diverter runs a metering operation. It is not the timing difference between the diverter moving in and out.

Assume：1) The flow characteristics of the diverter are symmetrical；2) Start and stop metering at point C (in the centre of the nozzle slot). The above two symmetries are called "ideal symmetry" conditions, the timing error of diverters is equal to zero, i.e. $\Delta t$ = 0 in theory. This is because the totalized flow in the metering duration is the area surrounded by C-C' -C'- C, since F1 = F2, F3 = F4, as shown in figure 3.

However, in general，1) It is difficult to start metering at point "C" , the center of the nozzle, that is called " installation asymmetry" ,as that will cause timing error of diverters; 2) The flow characteristic curves of diverters are difficult to be completely symmetrical about the point "C", called "flow asymmetry", as that will also cause timing error of diverters. The timing error caused by the two asymmetry of diverters is $\Delta t = \Delta t_1 + \Delta t_2$, as shown in figure 2 and figure 3.

It is also recommended by JJG164 to use a timing difference method to evaluate the uncertainty of diverters. We hold that this approach is debatable. Set the time of moving in (to the weighting tank) of a diverter as $t_2$ and the one of moving out (to the bypass) as $t_2'$, then, the timing difference is $\Delta t' = t_2 - t_2'$ , as shown in figure 2 and figure 3. Firstly, it can be seen from figure 3 that even if the timing difference is 0, that is, $t_2 = t_2'$, the timing error caused by the two asymmetries of diverters cannot be eliminated. In fact, when the timing difference is 0, $\Delta t_1 = \Delta t_2$ , $\Delta t = 2\Delta t_{1,2}$.Secondly, we can note that even if the timing difference is ≠ 0, the timing error of diverters will not occur as long as the two ideal symmetry conditions are met.

In addition, the timing error of diverters also includes the followings. 1)The random error caused by dynamic delay response of the photoelectric switch itself；2) The random error caused by the randomness of diverters in a single movement. There are essential differences between the random error caused by the above two factors and the timing error caused by the two symmetry factors of diverters, which must not be confused with each other. The timing error of diverters in the present paper refers to the error caused by the two asymmetry factors. It belongs to systematic error, which can be corrected as a correction quantity in practical applications.

*3.2 Derivation of timing error equations*

The timing error of diverters can be determined by the combination of a long-time standard metering diversion and a series of *n* short-time diversions (bursts).

Assume that the timing error of diverters for a single diversion is $\Delta t$, and the $\Delta t$ for any diversion is constant at a given flowrate. $q_0$ is the flowrate during a long-time standard diversion , $q_n$ is the mean flowrate determined during a series of *n* short time diversions , then

$$\begin{cases} q_0 = \dfrac{m_0}{t_0 + \Delta t} \\ q_n = \dfrac{\sum_{i=1}^{n} \Delta m_i}{\sum_{i=1}^{n} t_i + n \cdot \Delta t} \end{cases} \tag{6}$$

Where, $m_0$, $t_0$ are the liquid mass measured by the weighing machine and the corresponding metering time respectively while the diverter runs a long-time standard diversion. $\sum_{i=1}^{n} \Delta m_i, \sum_{i=1}^{n} t_i$ are the totalized liquid mass and the totalized time for *n* short-time bursts respectively.

The timing error $\Delta t$ of diverters can be obtained from Eq. (6):

$$\Delta t = \frac{t_0 \left(q_0/q_n\right)\left(\sum_{i=1}^{n} \Delta m_i \Big/ m_0\right) - \sum_{i=1}^{n} t_i}{n - \left(q_0/q_n\right)\left(\sum_{i=1}^{n} \Delta m_i \Big/ m_0\right)} \tag{7}$$

Set the meter factor of the flowmeter installed on the circuit is K, $q_0 = N_0 / K t_0$ , $q_n = \sum_{i=1}^{n} N_i \Big/ K \sum_{i=1}^{n} t_i$ , After substituting Eq.(7), we can get Eq.(8), that is the computational equation of timing error of diverters given by JJG164-2000 (flowmeter method).

$$\Delta t = \frac{t_0 \left[ N_0 \Big/ \sum_{i=1}^{n} N_i - m_0 \Big/ \sum_{i=1}^{n} \Delta m_i \right]}{\left[ n \cdot m_0 \Big/ \sum_{i=1}^{n} \Delta m_i \right] \cdot \left[ t_0 \Big/ \sum_{i=1}^{n} t_i \right] - \left[ N_0 \Big/ \sum_{i=1}^{n} N_i \right]} \tag{8}$$

where, $N_0$ is the totalized number of pulses measured by the flowmeter during a long-time standard diversion. $N_i$ is the totalized number of pulses for *n* short-time bursts.

Rewrite Eq. (6) as:

$$\frac{\sum_{i=1}^{n} \Delta m_i \Big/ \sum_{i=1}^{n} t_i}{m_0 / t_0} \cdot \frac{q_0}{q_n} = \frac{1 + n \cdot \Delta t \Big/ \sum_{i=1}^{n} t_i}{1 + \Delta t / t_0}$$

Since $t_0 \approx \sum_{i=1}^{n} t_i, \left(\Delta t / t_0\right)^2 \approx 0$ , Substituting into the above equation, we can get

$$\Delta t = \frac{t_0}{n-1} \left[ \frac{q_0}{q_n} \times \frac{\sum_{i=1}^{n} \Delta m_i \Big/ \sum_{i=1}^{n} t_i}{m_0 / t_0} - 1 \right] \tag{9}$$

Eq. (9) is the equation for calculating the timing error given by ISO4185 (static weighing method). It can be seen that the Eq. (9) is a simplified form of Eq. (8), and they are the same.

## 4. Experiments

*4.1 Experimental device and the principle*

The present experimental apparatus consist of sump, pump, flow diverter, weighing tank, electronic weighing scale, flowmeter and control system. The schematic of the experimental device is shown in figure4. The physical map of the diverter system is shown in Figure5. A stepping motor instead of traditional cylinder driving system is used in the device. The driving system of the diverter is composed of the stepping motor controlled by PLC and the screw rod slider mechanism. A fishtail shaped nozzle with DN25 arc line is selected for the test. The nozzle slot size is L = 8mm, b = 150mm.

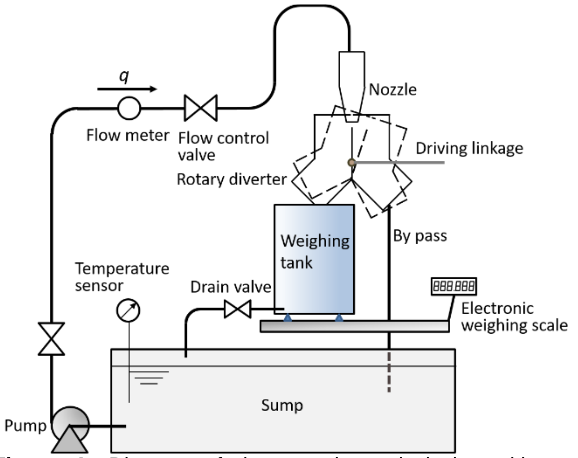


**Figure 4:** Diagram of the experimental device with static weighing method.

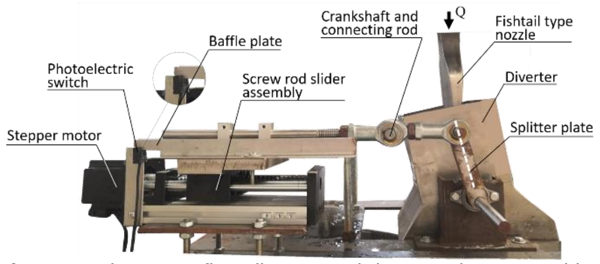


**Figure 5:** The rotary flow diverter and the stepping motor drive system.

A photocell signal trigger system is designed, which meets the condition of “ideal symmetry”, as shown in figure6. When the edge of the baffle plate passing through the mid position of a photoelectric switch, the wing is just in a vertical position, while its tip is at the mid-travel position of the nozzle slot. The baffle plate is just in the "O-C" position as shown in Figure 1.

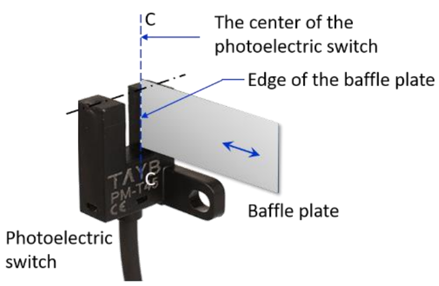


**Figure 6:** Photoelectric switch signal system.

The photoelectric switch that triggers the synchronous signal is one of the important apparatus in achieving a high-accuracy liquid flowrate. The main photoelectric switch parameters used in the experiment are shown in table 1.

**Table 1:** Main specifications of the photoelectric switch.

| Item | Specifications |
|---|---|
| Hysteresis(mm) | 0.05 |
| Repeatability(mm) | 0.01 |
| response time(μm) | Linght:20<br>Dark: 80 |

FX2N-1PG positioning module is used to drive the stepping motor. Set the driving parameters, as shown in Table 2.

**Table 2:** The stepper motor driving parameters.

| parameters | Specifications |
|---|---|
| Acceleration time (ms) | 50 |
| Operating speed (m/s) | 0.1 |
| Deceleration time (ms) | 50 |
| Distance (mm) | 20 |

It is seen from table 2 that after the diverter is started, it first accelerates for 50ms and travels a distance of 5mm. And then it travels at a constant speed of 0.1m/s for a distance of 10mm(>8mm) by programming, which ensures that the splitter plate of the diverter travels at a constant speed while passing through the width of the nozzle slot. Finally, the diverter slows down until it stops. The metering duration of one start-stop cycle of the diversion is 200ms. The driving speed curves are shown in Figure 3. Since the splitter plate passes through the nozzle slot at a constant speed, the diverter in the experiment has the optimal flow characteristics.

At the same time, the tests of the timing error caused by “installation asymmetry” were carried out. During the test, we installed the baffle plate at the C-C position of the centre point (called symmetrical installation condition) and the S-S position deviated from the centre point (called asymmetric installation conditions), as shown in figures 2 and 3.

The tests were carried out twice at the maximum and minimum flowrate respectively. Limited to the length of the article, the present paper only gives the maximum values of the two tests.

### *4.2 Data analysis*

In the present experiments, an electronic weighing scale was used with buoyancy corrected (correction factor $\varepsilon$=1.00106). The liquid was pure water, the water temperature was 21.0 ℃ during the test. Thus, the density of water was taken as $\rho$= 998.021 kg/m$^3$. The present paper only gives and analyses the experimental data of 0mm (symmetrical), - 8mm, - 5mm (early triggering) and + 5mm and + 8mm (delayed triggering) away from the centre of the nozzle slot at the flowrate of 7m$^3$/h, as shown in table3. Without considering the correction of flow variability during the test, we set $q_0/q_n$ =1.

**Table 3:** Experimental data of timing error of the diverter.

| Timing error | Negative deviation -8mm | Negative deviation -5mm | No deviation 0mm | Positive deviation +5mm | Positive deviation +8mm |
|---|---|---|---|---|---|
| $\sum_{i=1}^{n} \Delta m_i$ /kg | 86.3715 | 84.2092 | 88.4837 | 85.1602 | 84.4895 |
| $\sum_{i=1}^{n} t_i$ /s | 41.5292 | 39.8118 | 40.8644 | 38.6445 | 37.3383 |
| $m_0$/kg | 85.6106 | 86.6918 | 85.0801 | 86.4415 | 84.7998 |
| $t_0$/s | 40.3511 | 40.305 | 39.1794 | 40.0641 | 39.0344 |
| $n$ | 10 | 10 | 10 | 10 | 10 |
| $\Delta t$/ms (ISO4185) | -88.471 | -74.358 | -13.130 | 95.118 | 180.423 |

It can be seen from the experimental results in table 3, the timing error of the diverter is - 13.1 ms, when the baffle plate of the diverter system does not deviate. It shows that there are still some asymmetric conditions in the diverter system, which can be corrected in practical applications. The timing error will produce a negative deviation of -74.4ms when the baffle plate of the diverter system is installed - 5mm in advance from the center point. It will produce a positive deviation of 95.1ms when the baffle plate of the diverter system is installed + 5mm away from the center point.

## 5. Conclusions

1) The flow characteristic of rotary flow diverters depend on the driving method (such as the driving method of cylinder or stepping motor) and the driving law. The mathematical functions of flow characteristics of diverters were deduced.

2) The Birukov curves were obtained by assuming the cylinder moving at a constant acceleration. However, when the cylinder makes reciprocating movement (the diverter travels in and out), it must experience procedures from acceleration to deceleration until it stops, rather than running a single acceleration motion. Therefore, the ideal Biliukov curves do not occur.

3) It can be seen from the mathematical model of the flow characteristics of diverters that has been derived in the present paper, when the splitter plate of the diverter moves at a constant speed through the nozzle slot, the optimal flow characteristic curve of the diverter, that is, the nearly linear curves can be obtained.

4) The ideal symmetry condition of diverters is proposed as the installation requirement of the photoelectric switch in facilities. It is analyzed that the essence of the timing error of diverters is the error caused by installation asymmetry and flow characteristic asymmetry. The test and computational equations were deduced in the present paper. The theoretical analysis and the experiments show that when negative deviation occurs (triggered in advance), $\Delta t < 0$, and when positive deviation (lag triggered), $\Delta t > 0$. And the greater the distance from the center point, the greater the $|\Delta t|$.

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