STUDY ON FLOW SENSORS ARRANGEMENT OPTIMIZATION BASED ON THE MOBILE FLOW MEASURING DEVICES

YI ZHOU
College of Water Resources & Civil Engineering, China Agricultural University, 17 Tsinghua East Rd., Haidian District
Beijing, 100083, China

XUECHUN ZHANG
College of Water Resources & Civil Engineering, China Agricultural University, 17 Tsinghua East Rd., Haidian District
Beijing, 100083, China

YUHUI YANG
College of Water Conservancy & Architecture Engineering, Tarim University, Alaer
Xinjiang Uygur, 843300, China

YU HAN*
College of Water Resources & Civil Engineering, China Agricultural University, 17 Tsinghua East Rd., Haidian District
Beijing, 100083, China

In order to study the flow-measuring device with high precision and simple structure, spindle-shaped flow-measuring columns with different proportions were designed based on cylinder flow-measuring columns. The water metering performance of a spindle-shaped water metering column in a U-shaped channel was studied using numerical simulation and experimental study. Based on numerical simulation, three spindle-shaped water columns with different proportions are designed and simulated under different working conditions. Observe the three-dimensional flow pattern of water flow in a U-shaped channel, and analyze the head loss of spindle-shaped water column with different proportions. Based on the hydraulic characteristics of the spindle-shaped water column, the flow measuring mechanism is deduced, and finally, it is determined that the spindle-shaped water column with an aspect ratio of 2.5 has better water measuring performance. Furthermore, experimental studies were conducted in a U-shaped channel to determine the water depth extraction point during spindle water metering and to verify the hydraulic characteristics and water metering performance of spindle water metering. To explore whether the device also works well in other channels, verification tests were also carried out in the rectangular open channel. The results show that it is suitable for different cross-section types of open channels, which provides a reference basis for meeting the metering requirements of different open channels in actual projects.
Keywords: U-shaped open channel; flow-measuring column; flow measurement; numerical simulation; critical depth

1 INTRODUCTION

A key focus for smart irrigation districts to be able to operate effectively is to measure and monitor fluid flow [1]. Accurate water measurement ensures proper diversion of water. The transmission canals accurately distribute the referenced water. Therefore, it is crucial to investigate water measurement facilities that are highly accurate and simple in construction. The current smart open channel flow measurement devices are very expensive to build and install. Orifice plates, weirs, or measuring flumes are all that are needed to measure the flow in open channels. These devices often require proper maintenance. These devices measure flow primarily by creating a constriction of flow at the sides or bottom, thus effectively changing the three-dimensional flow pattern of the channel fluid. The principle of flow measurement is the nature of the critical flow. By installing an appropriate device with known geometry, the flow can be calculated by simply recording the depth of flow at one location.

Flow-measuring devices have been widely optimized and intensively innovated. Hager [2] first proposed the concept of a portable flow-measuring device, which can be applied to measure the discharge in rectangular, trapezoidal and U-shaped channels. Samani and Magallanez [3] put forward a design of half cylinder flume. The research realized shrinking the rectangular channels through attach two semicircular cylinders to the side wall of rectangular channel. He and Wang [4] tested nine kinds of cylinders with different shrinkage ratio on U-shaped channel and obtained the empirical formula of discharge calculation under the condition of free outflow. For channels with two semicircular cylinders on the sidewalls, Ghare and Badar [5] proposed a flow prediction model based on experiments. Kolavani et al. [6] and Bijankhan and Ferro [7] established a water level relationship with discharge in a tank with central baffle using dimensional analysis.

Equipment equipped with various sensors is commonly used to measure the flow in irrigation areas. Optimal sensor placement for fluid flow is an important and challenging issue [8]. The Gap Proper Orthogonal Decomposition (POD) method was applied to the steam reformer model to determine the optimal number and location of sensors [9]. Taluja and Patil [10] studied a double S-type Coriolis mass flow sensor in a stainless steel tube to determine the optimal phase change. Deng et al. [11] discussed the optimal sensor placement (OSP) strategy based on deep neural networks (DNN), which selects the five most sensitive sensors and effectively reduces the number of sensors. Sashittal and Bodony [8] proposed to find sensor locations based on the accompanying gradient descent.

Many direct and indirect methods have been developed for measuring discharge in irrigation canals and natural rivers by reviewing the methods to obtain the discharge data. Dey [12] presented a method to estimate discharge from the end depth in subcritical and supercritical flows. Vougioukas et al. [13] proposed an innovative river discharge monitoring system based on a horizontal acoustic Doppler current profiler (H-ADCP). Yang et al. [14] proposed a flow measurement method based on the horizontal and vertical U-shaped canal flow velocity distribution patterns, i.e., the flow velocity of a cross-section can be found by measuring only three points on the centerline. Abrari et al. [15] proposed a new theoretical approach for computing the end depth ratio (EDR) relationship, from which the end depth discharge (EDD) can be computed. Three types of flowmeters were employed to compare the accuracy of flow measured [16], including PTF, acoustic Doppler profiler (ADP), and radar surface velocimeter (RSV). Khosravinia et al. [17] used various data-driven models to estimate discharge and end depth in the free overfall flow with trapezoidal sections. All the above methods have problems of application scope and simplicity. Therefore, this study hopes to give a reliable method to provide a good idea of flow measurement.

Spindle-shaped flow-measuring column was designed and its flow-measuring performance is further studied based on contents above with numerical simulation combined with experimental research. Further thoughts of previous researches are raised in this article. A spindle-shaped flow-measuring column is designed based on the cylindrical flow-measuring column. Furthermore, the water measuring performance of the spindle-shaped flow-measuring column in a U-shaped channel is studied using the method of numerical simulation combined with experimental research.

2 MATERIALS AND METHODS

2.1 Structure Design of A Spindle-Shaped Flow-Measuring Column

The design of spindle-shaped flow-measuring column is further developed based on the design of cylinder flow-measuring column and round head flow-measuring column. Liu et. (2014) improved the cylindrical flume by adding V-tails to reduce head loss, improve the accuracy of flow measurement and increase sediment transport capacity. V-tails are combined with cylinder from both the front side and the back which can optimize water measuring column and decrease the head losses in the process of the measurement of spindle-shaped flow-measuring column efficiently (Figure 1). The aspect radio of spindle-shaped flow-measuring column can be changed by adjusting the length of the tail fin.

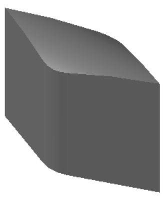


Figure 1. Structure diagram of spindle-shaped water column with V-tails

The main design parameters of the shuttle-shaped water measuring column body type are the diameter of the cylinder (i.e., the width of the cylinder) and the length of the V-wing. The height of the shuttle-shaped water measuring column frame is uniformly 30 cm, and the radius of the central cylinder is 10 cm. Figure 1 shows the specific form of the shuttle-shaped water measuring column. Define $\lambda = L/D$ as the ratio of the tail length of the shuttle-shaped water measuring column to the radius of the central cylinder. Here L can be geometrically interpreted as the distance from the center point of the shuttle-shaped water column to the endpoint of the tail. d is the width of the column and is the radius of the column in cm. the width of the water column in this paper is 10 cm, and three different aspect ratios are designed ($\lambda=L/D=3$, $\lambda=L/D=2.5$ and $\lambda=L/D=2$). The schematic diagram of the body shape parameters of the shuttle-shaped water measuring column is shown in Table 1.

Table 1. Design parameters of spindle-shaped water column

λ（λ=L/d）	*D*(cm)	*L*(cm)	*h*(cm)
2	10	20	30
2.5		25	
3		30	

2.2 Principle of flow measurement column for flow measurement

The flow measurement mechanism of the shuttle column is mainly based on the principle of critical flow. In this study, the shuttle-shaped column is installed at the axis of U-shaped channel, and the water flowing through the shuttle-shaped column partially narrows the cross-sectional area of the channel, which increases the flow velocity and forms a critical flow at the junction of slow flow and rapid flow, resulting in a single stable relationship between water depth and flow that is not affected by the downstream flow to achieve better flow measurement.

By comparing and analyzing the flow measurement mechanism of different types of water measurement devices, we combined various types of water measurement facilities and various portable water measurement devices with related research. The flow measurement mechanism of the shuttle-shaped water measuring column was deduced. After observing the placement of different types of water measuring devices, this study placed the shuttle-shaped water measuring column vertically at the centerline of the U-shaped channel. Combined with the water flow characteristics, the water flow in the upstream U-shaped channel in front of the column is slow-flowing, and when the water flows through the column, it contracts locally at its throat, it is affected by the lateral contraction, and the overflow section produces enough water surface drop and the water velocity increases. Therefore, the flow velocity and upstream water depth can be a single stable relationship, and the potential energy and kinetic energy are converted, and a critical flow is generated near the throat, followed by a rapid flow state, which articulates with the downstream flow. By observing the overflow characteristics of different types of volume water columns in the channel, it is clear that the flow rate and upstream head can constitute a single stable relationship.

The velocity distribution in the U-shaped channel is uniform, based on the energy equation, the specific energy of upstream measured flow section can be expressed as:

$$E_s = h_1 + \frac{\alpha Q^2}{2gA_1^2} \tag{1}$$

where E_s (m) represents specific energy of upstream flow section, Q (m^3/s) represents discharge in U-shaped channel, h_1 (m) represents upstream water depth, A_1 (m^2) represents upstream section area, α represents kinetic energy coefficient of correction(=1.0), g (m/s^2) represents gravitation constant.

The critical water depth is defined as the water depth corresponding to the minimum specific energy of the section. Considering the energy loss, when the flow rate, cross-section shape, and U-shaped channel size are set, according to the energy between the upstream section and the critical flow section, critical flow section specific energy can be given by Eq. (2):

$$E_k = E_s = h_k + \frac{\alpha Q^2}{2gA_1^2} + \frac{\beta Q^2}{2gA_1^2} \tag{2}$$

where E_k (m) represents critical flow section specific energy, h_k (m) represents critical depth, A_k (m^2) represents critical section area, β represents energy coefficient of correction, the meanings of other symbols are the same as previous.

$$F_r = \frac{v_k}{\sqrt{gh_k}} = 1 \tag{3}$$

$$Q = v_k A_k = \sqrt{g h_k} A_k \tag{4}$$

where F_r present the Froude number of critical flow section. Q (m^3/s) represents discharge, A (m^2) represents the critical section area. A_k can be calculated from the critical water depth h_k when the shape and size of the channel section area and the size of the measuring flume are known.

Theoretically, the over-tank flow can be calculated by Eq. (4) when the critical water depth is known. However, it is difficult to measure the critical water depth because the critical section will change with the flow rate, shrinkage ratio, and other factors. Therefore, based on the principle of energy conservation, the total upstream energy of the measured water column is used to calculate the over-tank flow rate. According to Eq. (2) and Eq. (3), the following equation can be obtained:

$$H_k = E_k = h_k + \frac{(\alpha+\beta) h_k}{2} \tag{5}$$

where H_k (m) represents depth of stagnation point, h_k (m) represents critical depth. According to Eq. (5), the total upstream energy has a one-to-one correspondence with the critical water depth, and the critical water depth has a one-to-one correspondence with the flow rate, so the over-tank flow rate can be calculated from the total upstream energy. After the installation of the shuttle-shaped measuring column, a standing water depth will be formed at the throat of the measuring column, and this study measures the flow through the standing water depth.According to Eq. (4) and Eq. (5), it can be obtained that:

$$Q = \sqrt{g h_k} A_k = \sqrt{\frac{2}{\alpha+\beta+2} H_k} A_k \tag{6}$$

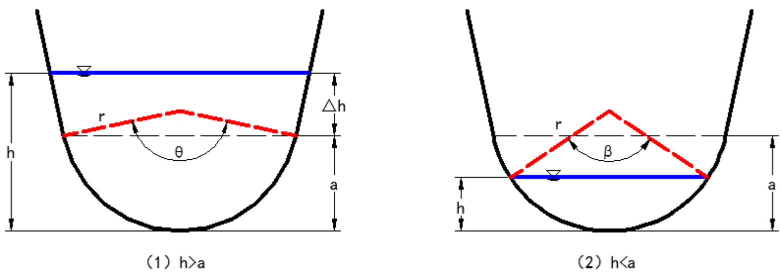


Figure 2. U-shaped channel cross-section. The section of U-shaped channel can be divided into arc section at the lower part and trapezoidal section at the upper part.

When the water level is in different sections, the form of the overflow cross section is different. The formula for calculating the hydraulic elements in different cases is also different, so the U-shaped channel cross-sectional area is in the form of segmental function. the formula for calculating the critical flow cross-sectional area A_k of U-shaped channel is as follows. When h_k > a and h_k < a, there exist:

$$A_k = \Delta h\left(\frac{2r}{\sqrt{1+m^2}} + \Delta h m\right) + r^2\left(\frac{\theta}{2} - \frac{m}{1+m^2}\right) \tag{7}$$

$$A_k = r^2\left(\frac{\beta}{2} - \frac{1}{2}\sin\beta\right) \tag{8}$$

where A_k (m^2) represents critical cross-sectional area, h_k (m) represents critical depth, $\triangle h$ (m) represents height of trapezoidal section, a (m) represents height of arc section, b (m) represents surface width, r (m) represents arc radius, θ (rad) represents center angle of bottom arc of cross section, β (rad) represents center angle og bottom arc of cross section, m represents slope coefficient of upper tangent section. Based on Eq. (7) and Eq. (8), considering total cross-sectional area of spindle-shaped flow-measuring column, critical cross-sectional area can be obtained as:

$$A_k = \Delta h\left(\frac{2r}{\sqrt{1+m^2}} + \Delta h m\right) + r^2\left(\theta - \frac{m}{1+m^2}\right) - A_b \tag{9}$$

$$A_b = b\left\{h_k - \left[r - \sqrt{r^2 - \left(\frac{b}{2}\right)^2}\right]\right\} + \left[r^2 \sin^{-1}\frac{b}{2r} - \frac{br}{2}\sqrt{1-\left(\frac{b}{2r}\right)^2}\right] \tag{10}$$

where b represents surface width at critical depth of spindle-shaped flow-measuring column. When stagnation depth H_k is known, discharge in channel can be calculated with Eq. (6), Eq. (9) and Eq. (10).

3 EXPERIMENT SETUP

3.1 Experiment of Measuring Point Arrangement for Critical Water Depth

The experimental research on a spindle-shaped flow-measuring column in a U-shaped channel was carried out in the hydraulic test hall of China Agricultural University, all the sizes were consistent with the numerical simulation. Ultrasonic Doppler velocimeter ADV current meter is used to measure water depth at measuring points. Actual figure and test layout of U-shaped channel are as for Figure 3.

The experimental study of the shuttle-shaped water column in the U-shaped channel was conducted in the hydraulic test hall of China Agricultural University. The overall dimensions of the U-shaped channel and the specific dimensions of the selected shuttle-shaped water column with an aspect ratio of 2.5 were consistent with the numerical simulation. The measurement equipment required during the test was an ultrasonic Doppler velocity meter ADV for flow velocity measurement and a moving stylus for water depth measurement at the measurement point.

During the test, the water flow is controlled by the control equipment of the channel, including pumps and inverter boxes, while maintaining a stable flow state at the same flow rate before measurement. The overall channel in addition to measuring equipment, control equipment also includes the water supply pipeline, return pipeline, and other components of the circulation system. The circulation system draws water from the storage tank at the beginning of the test, flows into the water stabilization tank through the delivery pipe, enters the 7.0m U-shaped channel in the whole field after flowing through the stabilization grille; and flows into the return tank at the end of the channel, and finally flows back to the storage tank to realize the water circulation system of the overall U-shaped channel. The layout of the test system and the main equipment are shown in Fig. 3. The U-shaped channel cross-section used in this test is shown in Table 2. The U-shaped channel is fixed on the steel structure support, and the bottom slope of the channel is adjusted by the spiral structure.

Table 2. Specific dimension parameters of the U-shaped channel

Center Angle at Bottom Arc(°)	Radius at Bottom Arc(m)	Height of the Channel(m)	Inclination of Lateral Wall of the Channel(°)	Width of Top of the Channel(m)
156	0.25	0.45	12	0.6

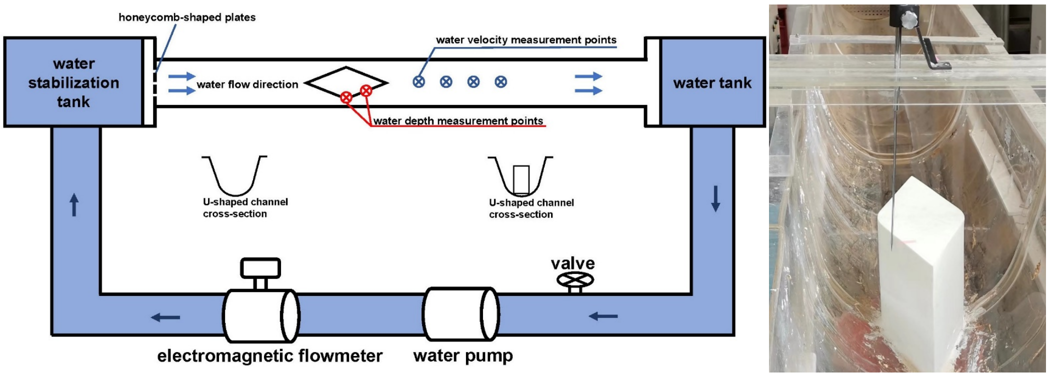


Figure 3. Measuring arrangement of spindle-shaped column and moving stylus in the U-shaped channel

Operating conditions for different discharges are determined with the discharge range of 20 m^3/h to 45 m^3/h. The flow velocity is measured at midline downstream and the feasibility of the numerical simulation is further verified by comparing it with the simulated flow velocity. Meanwhile, water depth measurements are carried out at two measuring points respectively, and discharge is calculated for error analysis and comparison with simulation results.

Table 3. Test conditions setting of U-shaped channel

Test number	Channel Flow (m^3/h)	Water depth (m)	Water surface width (m)	Cross-sectional average flow rate (m/s)
1	20	0.115	0.423	0.1672
2	25	0.127	0.435	0.1782
3	30	0.138	0.447	0.1890
4	35	0.149	0.457	0.1981
5	40	0.162	0.468	0.2017
6	45	0.172	0.475	0.2089

3.2 Channel Flow Analysis Based on Numerical Simulation

The three-dimensional model was made with CAD software. Overall dimension parameters were consistent with the simulation. Numerical simulation mainly creates three-dimensional flow in a U-shaped channel. Flow in the channel is the largely uniform flow which is flow in an open channel. The flow follows basic flow law: the law of conservation of mass, the law of conservation of energy, and the law of conservation of momentum. Indirect simulation is often used in numerical simulation of turbulent motion currently. Among all the indirect simulation methods, the RANS model is one of the significant ones and it is also a large branch in the whole turbulence model field. The divergence ratio of flat and cylindrical jet-flow can be predicted more accurately with the Realizable model, which is widely used in this field. The multinomial flow model is used in numerical simulation as a U-shaped channel containing two kinds of media: water and air. Meanwhile, the VOF method is used to obtain high fidelity free surface in numerical simulation, as the free surface of the open channel is a gas-liquid two-phase fluid bounding surface. In summary, the VOF polynomial flow model will be used in this study to track the free surface of the U-shaped channel water flow and further combine the two-equation Realizable k-ε model for calculation.

The ANSYS Meshing module was selected for this simulation and a tetrahedral mesh form was chosen for the dissection. First, the global mesh is set up and the mesh is dissected for the computational fluid. Some settings are also made for the optimized mesh size, and the body expansion rate is chosen to be 1.2, using the mesh damage judgment. After dividing the mesh, the different boundaries are named, such as water-in, air-in, etc. The grid division specifics are shown in Figure 4.

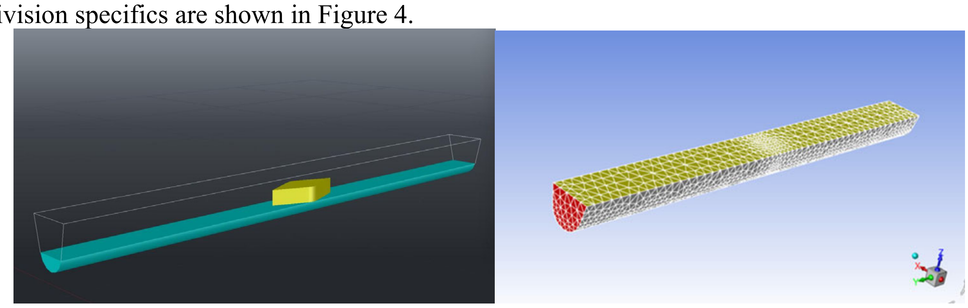


Figure 4. Overall model diagram of U-shaped channel.

After selecting the solution model for numerical simulation, the boundary conditions of the whole model need to be further set. The boundary conditions of the model mainly refer to the variables that change the law at the boundary of the model solution domain, including a series of change formulas with time and space. Since different boundary condition settings will have a large impact on the final numerical simulation results, it is necessary to ensure the reasonableness of the boundary condition settings in the numerical simulation process. According to the model situation and the required calculation results, five kinds of boundary conditions are set. First, for the inlet boundary: the air inlet section is set as the pressure inlet boundary, and the lower flow inlet, i.e., the inlet boundary at the end of the flow direction, is set as the flow inlet boundary, and the velocity is 0.138 m/s. The outlet section is given the pressure outlet boundary condition, and the pressure is assumed to be uniform. The upper surface of the model is set as the symmetric boundary, also called the free surface boundary, and the normal velocity and normal gradient of all other variables in this boundary are zero. The entire bottom and sidewalls of the channel are impermeable walls and are set as wall boundaries. No-slip boundary conditions are used in this turbulence model, and the distribution of velocity and turbulence within the boundary layer is represented by wall functions.

4 RESULTS

The 3D channel model was imported into ANSYS software channel flow field for numerical simulation. This can reduce the prototype test time and research cost, and also provide a more comprehensive and in-depth analysis of the hydraulic characteristics of the pike volume water column based on the simulation results. The numerical simulation of the overall solution domain of the U-shaped channel is based on the above solution method. Where the time step is set to 0.01s and the final number of calculation steps is set to 40,000 steps for calculation. After the numerical simulation, the obtained simulation results were post-processed using Tecplot post-processing software and CFD post-processing software CFD-Post.

4.1 Velocity Distribution in U-shaped Channel

The flow velocity distribution pattern of the flow field in a channel containing a shuttled column can be obtained by numerical simulation. Numerical simulations provide a wealth of information and details of the flow field. Figure 5 and Figure 6 show the longitudinal flow velocity and transverse flow velocity profiles of the water flow in the U-shaped channel with different flow rates.

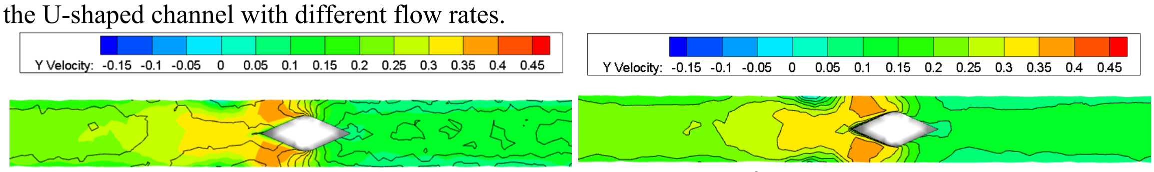


Figure 5. Flow velocity distribution in the vertical direction with Q=30m^3/h (a) Flow velocity distribution in the 1cm plane from the water surface. (b) Flow velocity distribution in the3cm plane from the water surface

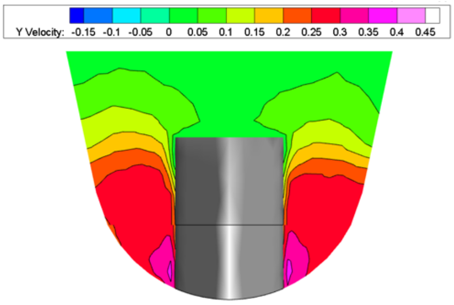


Figure 6. Cross-sectional flow velocity distribution (Q=30m^3/h)

By analyzing the 3D velocity distribution of the spindle-shaped flow-measuring column, water measuring performance of it can be better studied, which is more convenient for the structural optimization of the spindle-shaped flow-measuring column. In the overall U-shaped channel, the upstream velocity of the flow-measuring column is low and relatively uniform. Meanwhile, in the flow area near the upstream of spindle-shaped flow-measuring column, as the flow continues to approach the flow-measuring column, the flow velocity on both sides of the flow-measuring column keeps increasing while flow velocity in the middle of the channel keeps decreasing. After the flow on both sides of the spindle-shaped flow-measuring column is separated from the column, flow velocity continues to increase, reaching the maximum velocity at a certain distance behind the flow-measuring column. Then, the flow diffuses rapidly, and forms a hydraulic jump. The flow particles which are at hydraulic jump section are continuously mixed and collided, while flow velocity is redistributed and finally returns to uniform state.

4.2 Turbulent Dissipation Rate and Head Loss

When the water flows through the shuttle-shaped portable volume water column, the water flow structure changes dramatically, resulting in large energy losses. To study the head loss of the water flow in the size-shaped column more comprehensively, the turbulent kinetic energy dissipation rate is studied by numerical simulation with the help of FLOW software.

The distribution of the turbulent energy dissipation rate of the water flow in the shuttle-shaped column is shown in Figure 7. The water flow in the upstream of the shuttle-shaped column is in a slow flow state, the shape and size of the boundary of the water flow do not change along the way, and the head loss is small; the shape and size of the boundary of the water flow through the column change, the flow line bends, resulting in a larger local head loss, the turbulent energy dissipation rate increases, and the head loss increases; the water flow in the side plate of the shuttle-shaped column After the sidewall separation occurs at the outer edge of the shuttle-shaped water measuring column side plate, the flow line near the center of the channel is bent to a greater extent and the turbulent kinetic energy dissipation rate is larger. At a certain distance downstream of the measuring tank, the turbulent energy dissipation is accelerated due to the intersection of the water flow on both sides of the channel and the constant mixing of the water masses, which results in a higher turbulent energy dissipation rate and a higher head loss.

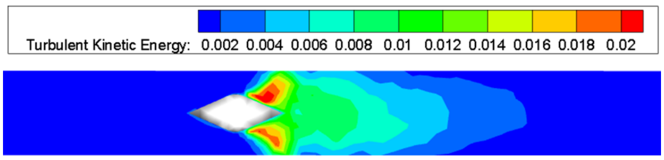


Figure 7. Variation of turbulent energy dissipation rate of channel flow

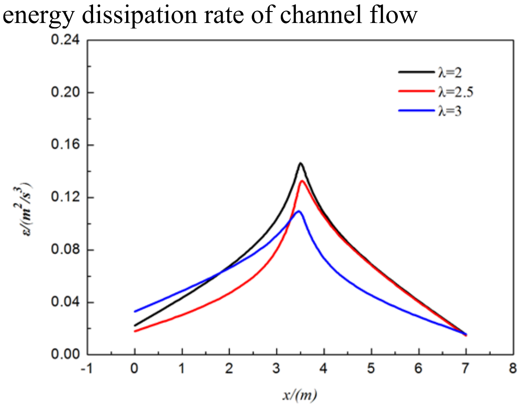


Figure 8. Comparison of turbulent dissipation rate of water column

The conditions of turbulent kinetic energy dissipation rates of different aspect ratios were compared, and the turbulent kinetic energy dissipation rates of different scales of the bobbin volume water column are shown in

Figure 8. The upstream and downstream slow flow cross-sections 1.5m away from the center of the channel are selected respectively, and the water depth is extracted, and the head loss of different proportional bobbin volume water column is calculated based on the upstream and downstream water level difference, as shown in Table 3.
Table 3. Head loss upstream and downstream of the shuttled volume column with different λ

Q (m^3/h)	λ	h_1 (m)	h_2 (m)	Δh (m)	Head Loss (%)
30	2	0.14291	0.13067	0.01224	8.565
	2.5	0.14240	0.13355	0.00885	6.215
	3	0.14065	0.13281	0.00784	5.574

where h_1 is sectional water depth at 1.5m from upstream to channel center, h_2 is sectional water depth at 1.5m from downstream to channel center, Δh is the hydraulic gradient between upper and lower reaches, λ is the aspect ratio of the spindle-shaped water column. According to Table 3, the spindle-shaped flow-measuring column with an aspect ratio of 3 has the smallest head loss. Combined with measuring precision, we can get a spindle-shaped flow-measuring column with the best ratio.

4.3 Collaboration of Critical Depth and Model

According to the 3D flow movement obtained by numerical simulation and the flow measuring mechanism of a spindle-shaped flow-measuring column, critical water depth measuring points are obtained (Figure 9).

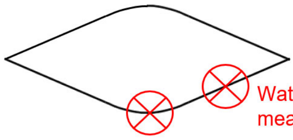


Figure 9. Critical water depth measuring point

The water depth at the corresponding location is extracted from the numerical simulation results. Select iso-surface in CFD software and set the air volume fraction to 0.5 to extract the water-air interface. Extract critical depth to calculate discharge from three spindle-shaped flow-measuring columns with different aspect ratios, compare and analyze measuring errors and measuring capabilities. Select the model with the smallest error for further research. Errors of the flow-measuring column with different aspect ratios are as Table 4, where $Q1$ represents actual discharge, $Q2$ represents calculated discharge, $h1$ represents critical depth, Ak represents section area, λ represents aspect ratio.

Table 4-1(a) Error of flow measurement by shuttled column with different aspect ratios（No.1 Measuring Point）

Q_1 (m^3/h)	λ	h_1（cm）	A_k（m^2）	Q_2（m^3/h）	Error (%)
30	3	5.97	0.0115	31.683	5.61
	2.5	5.89		31.469	4.89
	2	6.13		32.104	7.01

Table 4-2(b) Error of flow measurement by shuttled column with different aspect ratios（No.2 Measuring Point）

Q_1(m^3/h)	λ	h_1（cm）	A_k（m^2）	Q_2（m^3/h）	Error (%)
35	3	7.09	0.0106	31.824	6.08
	2.5	6.98		31.578	5.26
	2	7.24		32.157	7.19

According to the table, the smallest error and the best measuring performance are obtained at the No.1 measuring point with a spindle-shaped flow-measuring column whose aspect ratio is 2.5, which will be used in further research under different discharges.

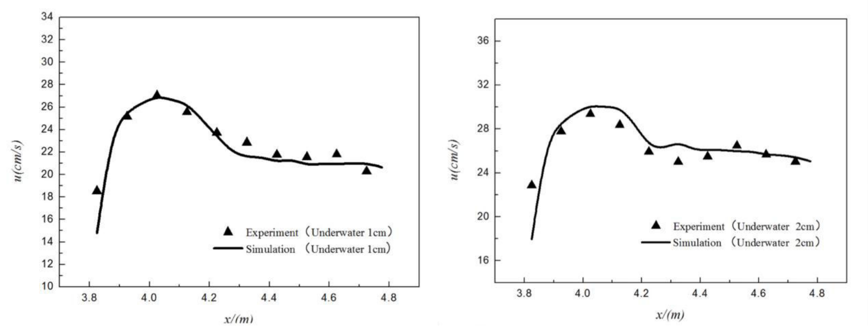
5 DISCUSSION

5.1 Analysis with Fitted Result of Velocity Distribution at Midline

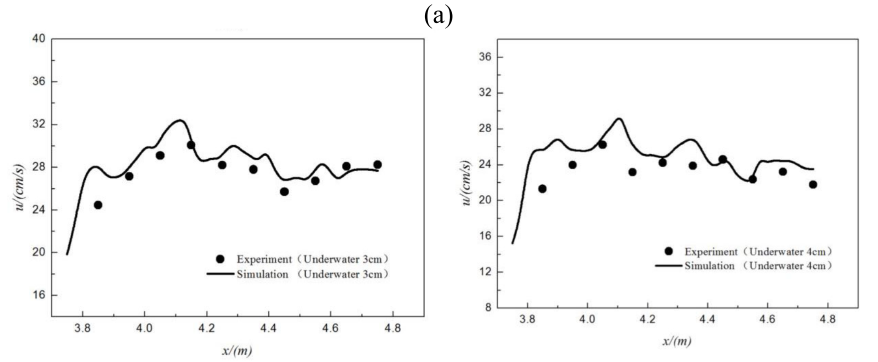
The actual channel dimensions at the time of the test are used as the overall computational domain, and all parameters in the computational model are kept consistent with the test. To further verify the reliability of the numerical simulation results, the simulated data of U-shaped channel with three working conditions of the flow rate of 30m3/h, 35m3/h, and 40m3/h, containing a shuttle-shaped volume water column with an aspect ratio of

2.5, are extracted and compared with the actual measured data on the vertical line in the U-shaped channel, and the specific comparison results are as follows. The specific results are as Figure 10.

Due to the existence of errors and the inevitable lack of detail in the setup of the numerical simulation, the situation reflected is not fully detailed. The numerical simulation results are consistent with the trend of velocity variation at the downstream centerline. Therefore, it can be assumed that the results of the numerical simulation can be used to extract the subsequent critical water depth.



(a)



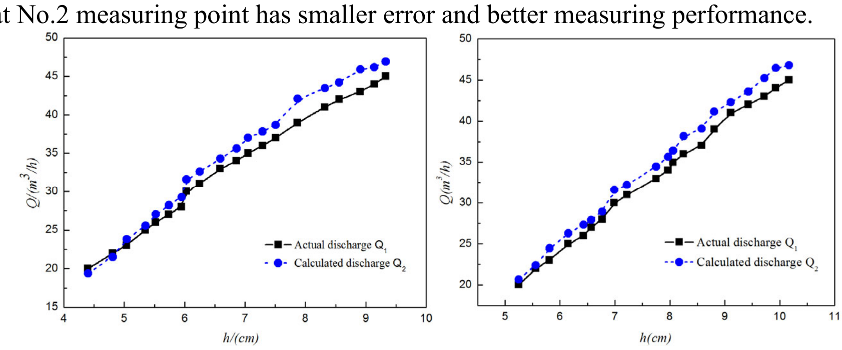
(b)

Figure 10. Test flow rate and simulation flow rate at center line. (a) Q=30m^3/h, (b) Q=35m^3/h

5.2 Critical Water Depth Extraction

As the position at critical depth is at the junction of supercritical and subcritical flow, its stability can be affected by the fluctuation of the surrounding water. According to the numerical simulation, critical depth can be represented by the depth measured under different discharges at No.1 and No.2 measuring points. The discharge in the U-shaped channel is calculated according to measured data and is compared with the actual discharge.

Uniform and stable flow is obtained by adjusting the pump frequency of the pump and controlling the manual valve on return pipeline. Water depth at the No. 1 and No. 2 measuring points can be obtained by moving the measuring needle. Depth-actual discharge diagram and depth-calculated discharge diagram at different measuring points (Figure 11) are obtained to analyse measuring capability of measuring column more accurately. From the numerical simulation results and experimental results, it is clear that spindle-shaped flow-measuring column with aspect ratio of 2.5 has better measuring performance. The error is around 5%. Furthermore, test data of different water depth at measuring points No.1 and No.2 are compared and analyzed. We conclude that No.2 measuring point has smaller error and better measuring performance.



(a) (b)

Figure 11. Results of channel calculated discharge compared to actual discharge. (a) at No.1 water depth measuring point (b) at No.2 water depth measuring point

6 DISCUSSION

This study has analyzed measuring performance of the spindle-shaped flow-measuring column in a U-shaped channel with numerical simulation and experimental research. Conclusions are summarized below:

(1) By comparing numerical simulation results and test results, it is found that the simulated data are in good agreement with the measured data and the maximum error is 6.350%. This shows that it is reasonable to use Realizable k-ε model and VOF multinomial flow model for numerical simulation of the spindle-shaped flow-measuring column in a U-shaped channel.

(2) According to the nephogram of flow velocity distribution in U-shaped channel obtained by numerical simulation, it's concluded that flow velocity is larger in the area close to side walls of channel. Under the blocking effect of spindle-shaped flow-measuring column, water flow at cross section of flow-measuring column shrinks to both sides of the channel when going downstream. At the same time, head loss in water measuring process of spindle-shaped flow-measuring column with different aspect ratio is compared and analyzed. The minimum head loss of spindle-shaped flow-measuring column with aspect ratio of 3 is 5.574%, and head loss of spindle-shaped flow-measuring column with aspect ratio of 2.5 is slightly larger as 6.215%.

(3) Numerical simulation shows that spindle-shaped flow-measuring column with aspect ratio at 2.5 has the smallest error and the best measuring performance. According to groups of data, the final calculated flow is close to actual flow, and error is around 5%, which further verified that the water measuring performance of spindle-shaped flow-measuring column with an aspect ratio of 2.5 is better.

REFERENCES

[1] Gupta H, Arumuru V, Jha R (2021): Industrial fluid flow measurement using optical fiber sensors: a review. IEEE Sens. J. 21, 7130-7144

[2] Hager WH (1985): Modified Venturi Channel. J Irrig Drain Eng 111, 19-35

[3] Samani Z, Magallanez H (2000): Simple flume for flow measurement in open channel. J Irrig Drain Eng 126, 127-129

[4] He W, Wang Y (2006): Cylinder flow measuring flume for U-shape channel. Journal of Hydraulic Engineering 37, 573-577

[5] Ghare AD, Badar AM (2014): Experimental studies on the use of mobile cylinders for measurement of flow through rectangular channels. Int J Civ Eng 12, 504-512

[6] Kolavani FL, Bijankhan M, Di Stefano C, Ferro V, Mazdeh AM (2019): Experimental Study of Central Baffle Flume. J Irrig Drain Eng 145

[7] Bijankhan M, Ferro V (2019): Experimental study on triangular central baffle flume. FLOW MEASUREMENT AND INSTRUMENTATION 70

[8] Sashittal P, Bodony DJ (2021): Data-driven sensor placement for fluid flows. THEORETICAL AND COMPUTATIONAL FLUID DYNAMICS 35, 709-729

[9] Jo T, Koo B, Kim H, Lee D, Yoon JY (2019): Effective sensor placement in a steam reformer using gappy proper orthogonal decomposition. APPLIED THERMAL ENGINEERING 154, 419-432

[10] Taluja R, Patil PP (2021): Positional optimisation of twin-S shape CMFS in stainless steel tube, MATERIALS TODAY-PROCEEDINGS, pp. 10349-10355

[11] Deng Z, He C, Liu Y (2021): Deep neural network-based strategy for optimal sensor placement in data assimilation of turbulent flow. PHYSICS OF FLUIDS 33

[12] Dey S (2002): Free overall in circular channels with flat base: a method of open channel flow measurement. Flow Meas. Instrum. 13, 209-221

[13] Vougioukas S, Papamichail D, Georgiou P, Papadimos D (2011): River discharge monitoring using a vertically moving side-looking acoustic Doppler profiler. Comput. Electron. Agric. 79, 137-141

[14] Yang S, Han J, Peng S, Han D (2012): Analysis and experiment of distribution properties and its application of velocity in U-shaped open channel. Trans. Chin. Soc. Agric. Mach. 43, 92-96

[15] Abrari E, Ergil M, Beirami MK (2019): Flow measurement using free over-fall in generalized trapezoidal channels based on one velocity point method. Flow Meas. Instrum. 69

[16] Chen FW, Liu CW (2020): Assessing the applicability of flow measurement by using non-contact observation methods in open channels. Environ. Monit. Assess. 192

[17] Khosravinia P, Nikpour MR, Kisi O, Yaseen ZM (2020): Application of novel data mining algorithms in prediction of discharge and end depth in trapezoidal sections. Comput. Electron. Agric. 170