ENERGY DISSIPATION CHARACTERISTICS OF AN IN-CHAMBER LONGITUDINAL CULVERT SYSTEM WITH THREE-LAYER SIDE PORTS DESIGNED FOR A LARGE-SCALE LOCK WITH 60M WATER HEAD

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Abstract:

With the rapid development of the water transportation industry in China, the scale of ships navigating in the inland waterway is increasing. However, the water head formed by dams is very high, especially for the hydroelectric projects constructed in the upper mountain river. Therefore, it is critically urgent to build several high-head and large-scale locks. Moreover, when the water head is increased to 60 m, huge water energy could be generated and then introduced into the corresponding lock chamber if the valve operating time is limited. This paper presented the in-chamber longitudinal culvert system with three-layer side ports to efficiently dissipate the water energy to ensure safe mooring conditions for ships during a lock operation. A three-dimensional CFD model for 1/4 local region of the corresponding chamber was developed to predict its hydraulic behavior. The numerical simulations were conducted to examine the effect of the vertical spacing between side ports on the energy dissipation result. Results showed that good energy dissipation performance was gained when the relative vertical spacing was set B/D=0.25 (B is the vertical spacing between side ports, D is the inner height of the culvert). Furthermore, the energy dissipation mechanism of this arrangement was presented based on the results of a three-dimensional hydraulic characteristic. In addition, the corresponding dissipation result of the present arrangement was compared with those of the single-layer and two-layer side ports. The dissipation performance of the present design was found to be the best if all the side ports' cross-section area of each arrangement keeps the same.

1 Introduction

As an ancient means of transportation, navigation has the advantages of high capacity and low cost. With the rapid development of the water transportation industry in China, the demand for navigation and the scale of ships navigating in the inland waterway are increasing. However, the water head formed by a dam is particularly high, especially for those hydroelectric projects constructed in upper mountain rivers. Currently,

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many locks having an operating water head of more than 35m have been built in China, such as the Wuqiangxi in the Yuanshui River, Shuikou Lock in the Minjiang River, Three Gorges Lock in the Yangtze River, Yinpan Lock in the Wujiang River, Datengxia Lock in the Qianjiang River and Angu Lock in the Daduhe River [1-4]. In the next decade, the plane dimension of the large-scale lock will have reached 1.2~1.4 times that of the Three Gorges Lock, and their maximum water head will also have reached 60m. However, when the water head is increased to 60m, huge water energy will be generated within a limited operation time of the valve and then introduced into the corresponding lock chamber, and the berthing safety of ships in the lock chamber will be seriously threatened. Therefore, to effectively dissipate energy within the limited water depth of the lock chamber and the specified filling/emptying time, and ensure the safe mooring conditions of ships during the lock operation, an in-chamber longitudinal culvert system with three-layer side ports is proposed in this paper.

At present, there have been only a few studies on the hydraulic behavior and energy dissipation characteristics of jets generated by different side port arrangements, and most of them focus on the single jet [5-7]. However, the outlet of side ports is part of multiple jets during the lock filling and emptying system operation. Kunz et al. [8] researched the transverse multiple jets and determined that under strong secondary flow and inlet conditions. The intense transverse diffusion of jets was observed due to the anisotropy of Reynolds stress. Perumal et al. [9] obtained the decay and diffusion characteristics of multiple jets and compared them with a single jet. In terms of the research on the in-chamber longitudinal culvert system with side ports, Wang et al. [10] studied the ship mooring force of the lock chamber under different arrangements of side ports in the in-chamber longitudinal culvert system using CFD code FLUENT, and its energy dissipation performance was consequently analyzed. Moreover, some types of side port arrangement were obtained, but a detailed study on the optimal arrangement (optimal number and spacing) of the side ports and the evolution law of flow distribution was not conducted. Simulated studies for a super-power lock filling and emptying system with a 60m water head were conducted by Li [11] using 3-D numerical simulation, and the energy dissipation mechanism was revealed by analyzing the energy dissipation characteristics under different layers of side port and vertical spacing between side ports and opening angles. The ideal energy dissipation was obtained for the two-layer side ports outlet with the upper-layer side ports downward inclination, and the relationship between the distance of the upper and lower side ports and the optimal opening angle was given. However, the mass-flow inlet of the study is constant, which is obviously different from the filling and emptying process of the lock. Studies for the three-dimensional hydraulic characteristics of the lock chamber were performed by Yang et al. [12] establishing the mathematical model for the lock filling and emptying system of 1/4 local region of the in-chamber longitudinal culvert system with an open ditch, and the distribution law of side ports discharge and the energy dissipation mechanism of the open ditch under different filling flow rate were revealed. The hydraulic characteristics and energy dissipation characteristics of the two-layer aligning side ports under different vertical spacing were studied by Miao [13] establishing the mathematical model for lock filling and emptying system of in-chamber longitudinal culvert system with two-layer side ports designed for the large-scale lock with 60m water head, the energy dissipation performance first become better and then worse within the vertical spacing of 2~5m, and the best energy dissipation result was obtained when the vertical spacing is 3m. The arrangement of multi-layer side ports, however, was not further studied.

It can be seen that when the two-layer side ports of the lock filling and emptying system are reasonably arranged, the jets will be mixed and an energy dissipation cushion will be formed between these jets during the lock filling process. As a result, the energy dissipation performance could be improved. If the multi-layer side port arrangement is adopted, the mixing will be theoretically increased to form a multi-layer energy dissipation cushion and obtain better energy dissipation performance. However, the research of the multi-layer (e.g., three layers) side port arrangement of the lock filling and emptying system has not been reported until now.

In conclusion, under the background that the lock tends to be large-scale and high-water head, the investigation of the in-chamber longitudinal culvert system having multi-layer side ports designed for the large-scale lock with the extremely high head is not sufficient. For example, the aforementioned studies have only focused on the single jet, single-layer, or two-layer side ports. In fact, the arrangement of multi-layer side ports has not been further studied. Thus, a three-dimensional numerical simulation was conducted in this paper to investigate the energy dissipation characteristics of an in-chamber longitudinal culvert system having three-layer side ports designed for the large-scale lock with a 60m water head under different vertical spacing between side ports. The remaining specific energy, flow velocity distribution uniformity, streamline characteristics, horizontal velocity contour distribution, and turbulent kinetic energy distribution on typical sections were presented. Meanwhile, the energy dissipation mechanism was analyzed, and the energy dissipation performance of three-layer side ports was compared with those of the single-layer and two-layer side ports.

2 Mathematical model

2.1 The RNG k-ε Turbulence Model

The RNG k-ε Turbulence Model is used in this paper. The anisotropic high-speed jet will be produced by side ports due to the effect of the side wall of an open ditch. Therefore, the RNG k-ε Turbulence Model [14-17] established by Yakhot and Orszag [18] is employed in this paper because it is suitable for the separation and rotation flow.

The free water surface of the lock chamber could be simulated better using the VOF model. The partial differential equations are discretized by the finite volume method and the pressure velocity coupling is solved by the PISO method. The solid wall boundary is treated by the wall function method. The CFD code fluent is used for solving partial differential equations.

2.2 Model Generalization and Meshing

The model in this paper is a large-scale lock with a 60m water head. The hydraulic characteristics and energy dissipation of the three-layer vertical side ports are investigated using the aforementioned turbulence model. The 1/4 filling area of the chamber is selected to generalize the model according to the symmetry layout of the filling and emptying system in the lock chamber due to the large overall scale of the lock, which includes four longitudinal culverts with single open ditches and is divided into two symmetry outlet parts. The specific chamber dimension adopted is 155 m × 20 m (length × width). The side ports are evenly arranged along the length of the lock chamber, as shown in Figure 1. Meanwhile, to ensure the rationality and effectiveness of the comparison between different arrangements, the constant total filling area of the side ports is kept.

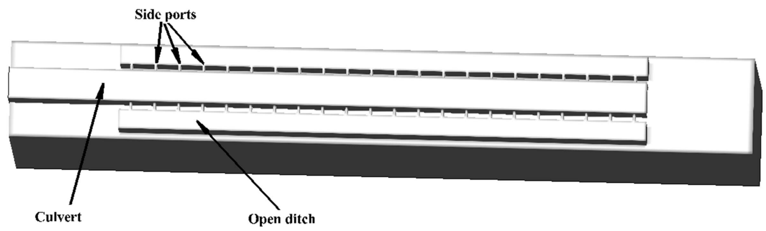
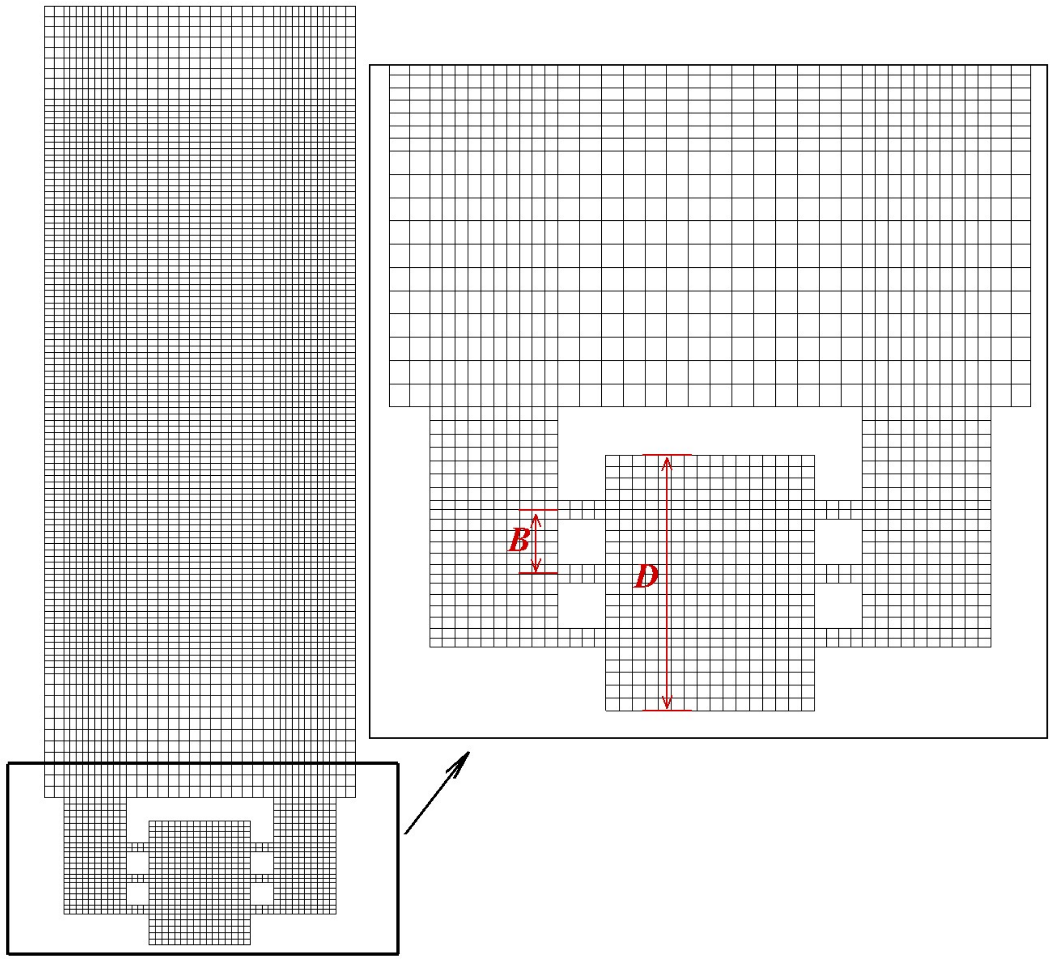


Figure 1. Three-dimensional model of a large-scale lock with 60m water head.

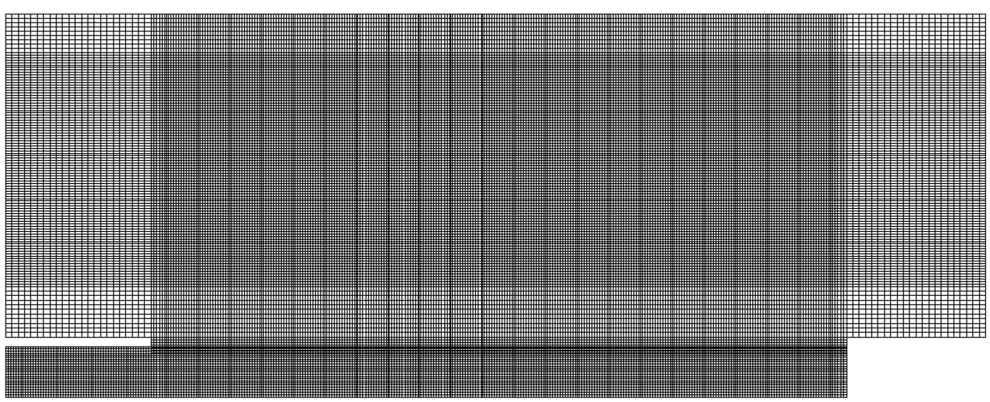
The cross and longitudinal sections of the generalized model grid of the CD3 (B/D=0.25, B is the vertical spacing between side ports, and D is the inner height of a culvert) (see the next section) are shown in Figure 2, which consists of hexahedral structural meshes. Local grid refinement is conducted in key research areas such as the outlet side ports, open ditch, and the middle of the lock chamber. The minimum and maximum spacings between adjacent grid nodes are 0.3m and 0.7m, respectively.

2.3 Calculation Cases and Arrangements of Side Ports

To study the hydraulic behavior and energy dissipation characteristics of the outlet of side ports on the side wall of the in-chamber longitudinal culvert, three-layer vertical aligning side ports are arranged in this paper. More specifically, 22 rows of side ports are arranged evenly according to the spacing of 5m in the longitudinal direction. The height of each side port is 0.57m, and the vertical spacings (B) between two adjacent layers are 1m, 1.5m, 2m, and 2.5m, respectively. The total number of side ports is 66 with a total area of 37.4m^2. The calculation cases are listed in Table 1, and the schematic diagram of the side port arrangement is shown in Figure 3.



(a)

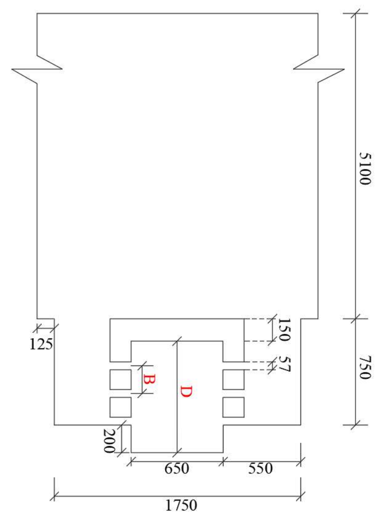


(b)

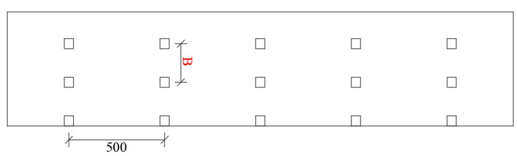
Figure 2. Schematic diagram of CD3, B/D=0.25: (a) cross section of model grid, (b) longitudinal section of model grid.

Table 1. Calculation cases.

Cases	Longitudinal spacing between side ports, m	Height of each side port, m	Vertical spacing between side ports (*B*), m	Inner height of a culvert (*D*), m	*B/D*
CD1	5	0.57	1.0	8	0.125
CD2	5	0.57	1.5	8	0.188
CD3	5	0.57	2.0	8	0.250
CD4	5	0.57	2.5	8	0.313



(a)



(b)

Figure 3. Schematic diagram of side ports: (a) cross-section of the lock chamber, (b) longitudinal section of the lock chamber. (All units in cm).

2.4 Boundary Conditions

The model of two flow outlet sections containing four secondary culverts with a central flow divider is adopted in this paper, which is symmetrically arranged in the lock chamber. The generalized model used for numerical simulation is 1/4 local region of the lock chamber. Subsequently, two symmetry planes are generated. Those symmetry planes are set as the symmetry boundary condition, and the inlet surface of the culvert located at the bottom of the lock chamber is set as the mass flow-inlet boundary. The corresponding time history of the filling flow rate is shown in Figure 4. The time range is 0~500s, including the initial filling time T=100s, the maximum remaining specific energy time T=310s, and the maximum flow rate time T=410s. The top of the lock chamber is set as the atmosphere pressure outlet because it is connected to the open air, as shown in Figure 5.

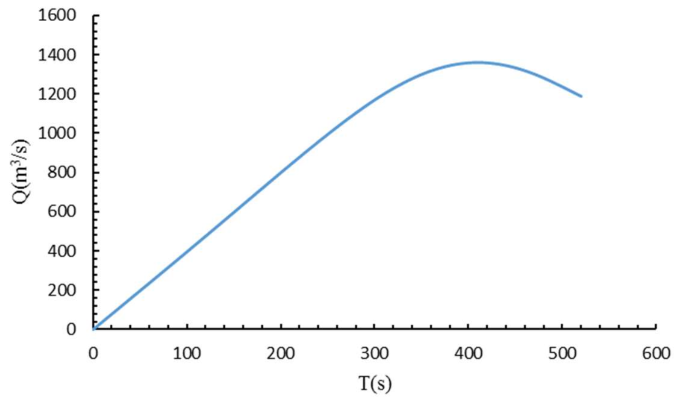


Figure 4. Time history of the flow rate at the inlet.

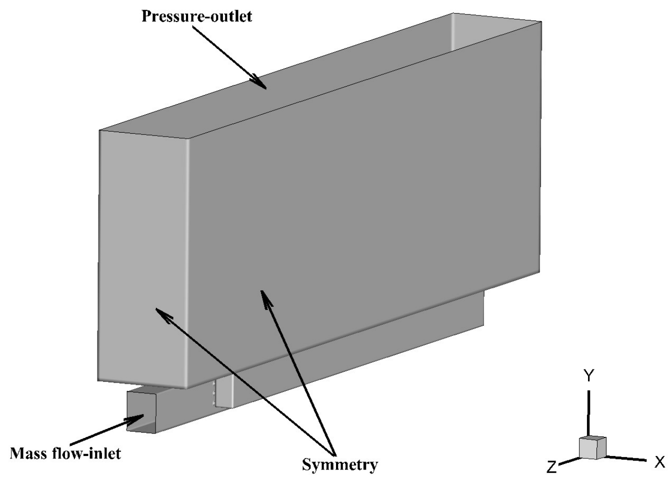


Figure 5. The boundary conditions of the generalized model.

2.5 Model Validation

The reliability of the model is validated by comparing the results of the CD4 (B/D=0.313) with the single-jet experimental data obtained by the physical model tests [19]. Figure 6 shows the spanwise and vertical velocity profiles on two typical cross-sections at a distance of 2L (1.75m, L is the square root of the area of the side port) and 4L (3.5m) from the side port. The jet velocity profiles collapse well with the physical model in the spanwise direction and in the vertical direction region $0<y/y_{1/2m}<1.5$, while slight deviation from the physical model is occurred in the vertical direction region $y/y_{1/2m}>1.5$.

The reason is that the width of the single open ditch in the model is 4m, and the length scale is 4.57L correspondingly, which is much smaller than the physical model. Therefore, the vertical velocity profiles in the upper region of the side port are easily affected by the recirculation generated by the jet impingement on the wall of the open ditch. In general, the results of the mathematical model established in this paper are in reasonably good agreement with the experimental data of the physical model. Therefore, the RNG k-ε Turbulence Model is capable of simulating the hydraulic behavior of the side ports in the lock filling and emptying system.

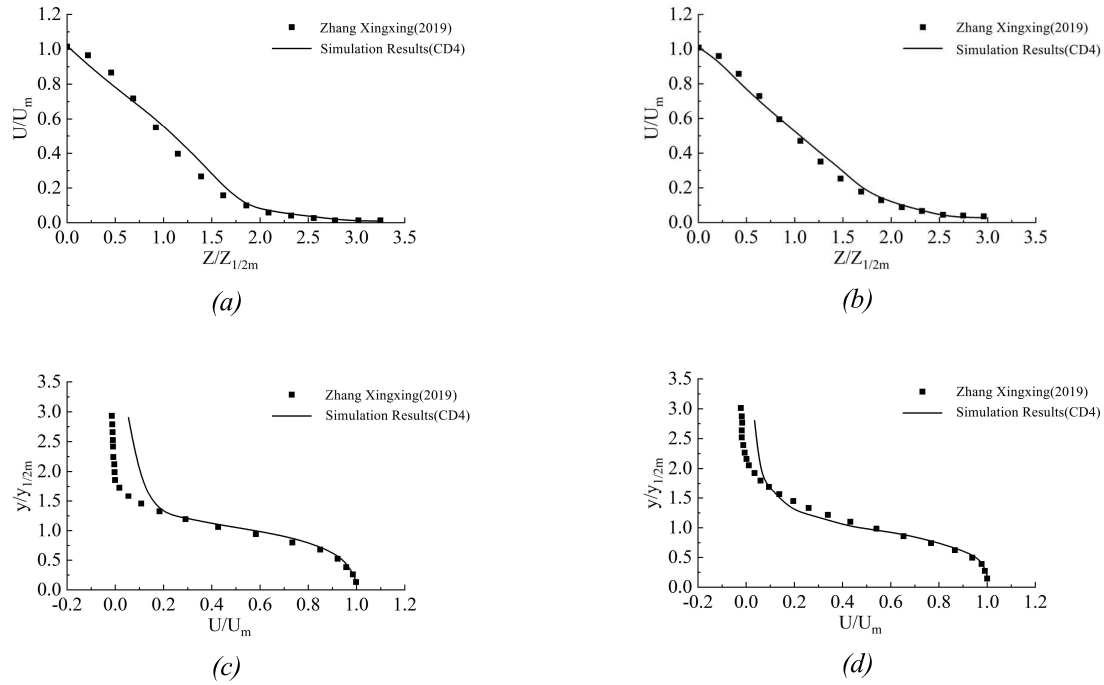


Figure 6. Velocity validation: In the spanwise direction of cross-section at (a) 2L, (b) 4L, and in the vertical direction of cross-section at (c) 2L, (d) 4L. U and Um are the velocity and maximum velocity on the cross-section, respectively, Z and $Z_{1/2m}$ are the spanwise coordinate value and spanwise velocity half-width, respectively, and y and $y_{1/2m}$ are vertical coordinate value and vertical velocity half-width, respectively.

3 Results

The hydraulic behavior at the two important times (the maximum remaining specific energy time, T=310s, and the maximum flow rate time, T=410s) is analyzed to study the influence of the different vertical spacing between side ports on the energy dissipation characteristics.

3.1 Remaining Specific Energy Analysis

The energy dissipation performance of three-layer vertical aligning side ports with the different vertical spacing and single open ditch arrangement could be effectively compared by analyzing the flow velocity distribution uniformity m and the remaining specific energy E_{pt}, which are on the horizontal cross-section at different water depths in the lock chamber. The remaining specific energy could be calculated by the equation [20]:

$$E_{pt} = \frac{\rho}{2} m v^3_{mt} \tag{1}$$

In the equation: v_{mt} is the average velocity on the cross-section at the time t, ρ is the density of water. m is usually used to represent the flow velocity distribution uniformity on the corresponding cross-section of the lock chamber, and could be calculated by the equation:

$$m = \frac{\int_{c_t} v^3{}_t dc_t}{c_t v^3{}_{mt}} \approx \frac{1}{n}\frac{\sum_{i=1}^{n} v^3{}_{ti}}{v^3{}_{mt}} \tag{2}$$

In the equation: v_i and c_i are the velocity of nodes on the cross-section and the area of the cross-section at the time t, respectively.

The remaining specific energy E_{pt} and flow velocity distribution uniformity m of the above 4 cases at the typical time, which are on the horizontal section at the region of 0.1H~0.8H (H is the water depth of the lock chamber at each typical time), were calculated by those aforementioned equations, respectively. It can be seen from Figure 7(a) that with the increase of vertical spacing between side ports (0.125≤B/D≤0.313), the remaining specific energy on each typical section (0.1H~0.5H) tends to first decrease and then increase at the time of maximum remaining specific energy (T=310s). With the increase of filling flow rate and the corresponding remaining specific energy on each typical section is increased in different degrees at the time of maximum flow rate (T=410s). Similarly, the remaining specific energy on each typical section (0.1H~0.4H) tends to first decrease and then increase with increasing vertical spacing between side ports, which is consistent with the change tendency of remaining specific energy at the time of maximum remaining specific energy (T=310s), as shown in Figure 7(b). The change tendency of flow velocity distribution uniformity on each typical section (0.1H~0.8H) varying with the increase of vertical spacing between side ports is consistent with that of remaining specific energy, as shown in Figure 8. In conclusion, both the remaining specific energy and flow velocity distribution uniformity are found to be the smallest when the relative vertical spacing is set B/D=0.25 (CD3), indicating that the energy dissipation performance is the best during the entire filling process.

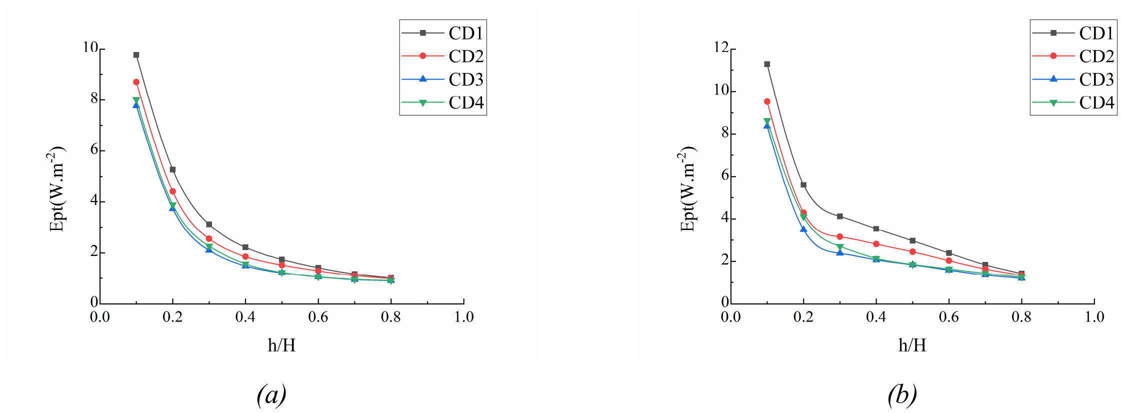
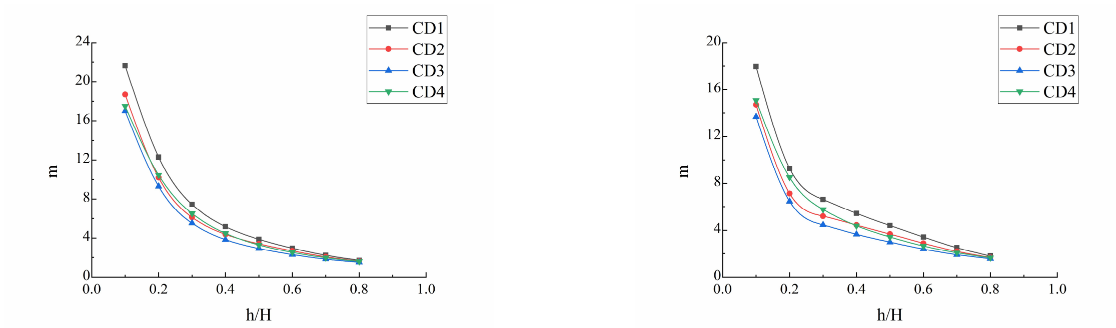


Figure 7. The remaining specific energy of CD1(B/D=0.125), CD2(B/D=0.188), CD3(B/D=0.25) and CD4(B/D=0.313): (a) is the remaining specific energy of CD1, CD2, CD3 and CD4 at maximum remaining specific energy time (T=310s), (b) is the remaining specific energy of CD1, CD2, CD3 and CD4 at maximum flow rate time (T=410s).



(a) *(b)*

Figure 8. The flow velocity distribution uniformity of CD1 (B/D=0.125), CD2(B/D=0.188), CD3(B/D=0.25) and CD4(B/D=0.313): (a) is the flow velocity distribution uniformity of CD1, CD2, CD3 and CD4 at maximum remaining specific energy time (T=310s), (b) is the flow velocity distribution uniformity of CD1, CD2, CD3 and CD4 at maximum flow rate time (T=410s).

3.2 Streamline Characteristics

To study the influence of different vertical spacings between side ports on the culvert on the energy dissipation performance, it could be analyzed from the vortex size in the lock chamber. When the filling flow rate reaches the maximum value (T=410s), the maximum outflow velocities of side ports of CD1, CD2, CD3, and CD4 are 8.97m/s、8.85m/s、8.87m/s and 8.86m/s, respectively. Figure 9 shows the distribution of streamlines in the cross-section. It can be clearly seen that streamlines in the lock chamber are basically symmetrical due to the symmetrical arrangement of side ports. Since the water with huge energy is being introduced into the lock chamber, vortex structures with different sizes are formed as a result of flowing water squeezed and sheared by the ambient low-speed water body in the lock chamber. Among them, two pairs of symmetrical energy-dissipation vortices are formed in the region -2m<X<8m, 10m<Y<16m, and on the lock wall 12m<Y<27m when the relative vertical spacing is set B/D=0.125(CD1), as shown in Figure 9(a), and a pair of energy-dissipation vortices is formed in the region -2m<X<8m, 10m<Y<15m when B/D=0.188(CD2), while the vortex structure on the lock wall is not obvious. Meanwhile, there is a small part of the water flows to the bottom of the lock chamber near Y=17m, as shown in Figure 9(b). As the vertical spacing increases further, a pair of energy-dissipation vortices are formed in the region -2m<X<8m, 10m<Y<16m when B/D=0.25(CD3), and in the region -2m<X<8m, 10m<Y<19m when B/D=0.313(CD4), as shown in Figure 9(c) and (d), respectively. It's not difficult to conclude that those vortices' size first decreases and then increases with increasing vertical spacing between side ports (0.125≤B/D≤0.313), which is found to be consistent with the change tendency of remaining specific energy and flow velocity distribution uniformity. As expected, the vortices size in the lock chamber is the smallest when the relative vertical spacing is set B/D=0.25(CD3), indicating that sufficient mixing and good energy dissipation performance in the open ditch is gained. The reason for the aforementioned change tendency is that for B/D=0.125(CD1) and B/D=0.188(CD2), which are relatively small, the jets produced by the side port impinge the outer wall of the open ditch and then turn to the inside of the lock chamber, resulting in insufficient energy dissipation, and the water with huge energy propagates in the form of wave oscillation along the inlet direction of the culvert, as shown in Figure 10(a) and (b). A confluence phenomenon, however, is formed in the region between the two adjacent layers of side ports by jets when B/D=0.25(CD3) and B/D=0.313(CD4), as shown in Figure 10(c) and (d). In the region, the water will be sheared and mixed to dissipate energy, resulting in the jet velocities of side ports decayed to about 0.80m/s and 0.90m/s when B/D=0.25 and B/D=0.313, respectively. The mixing strength between the two adjacent layers of the jet is weakened due to the excessive vertical spacing between the side ports when B/D=0.313. Moreover, a series of obvious energy-dissipation vortexes in the region between the two adjacent rows of side ports is formed due to the water energy has not been dissipated sufficiently, as shown in Figure 10(d).

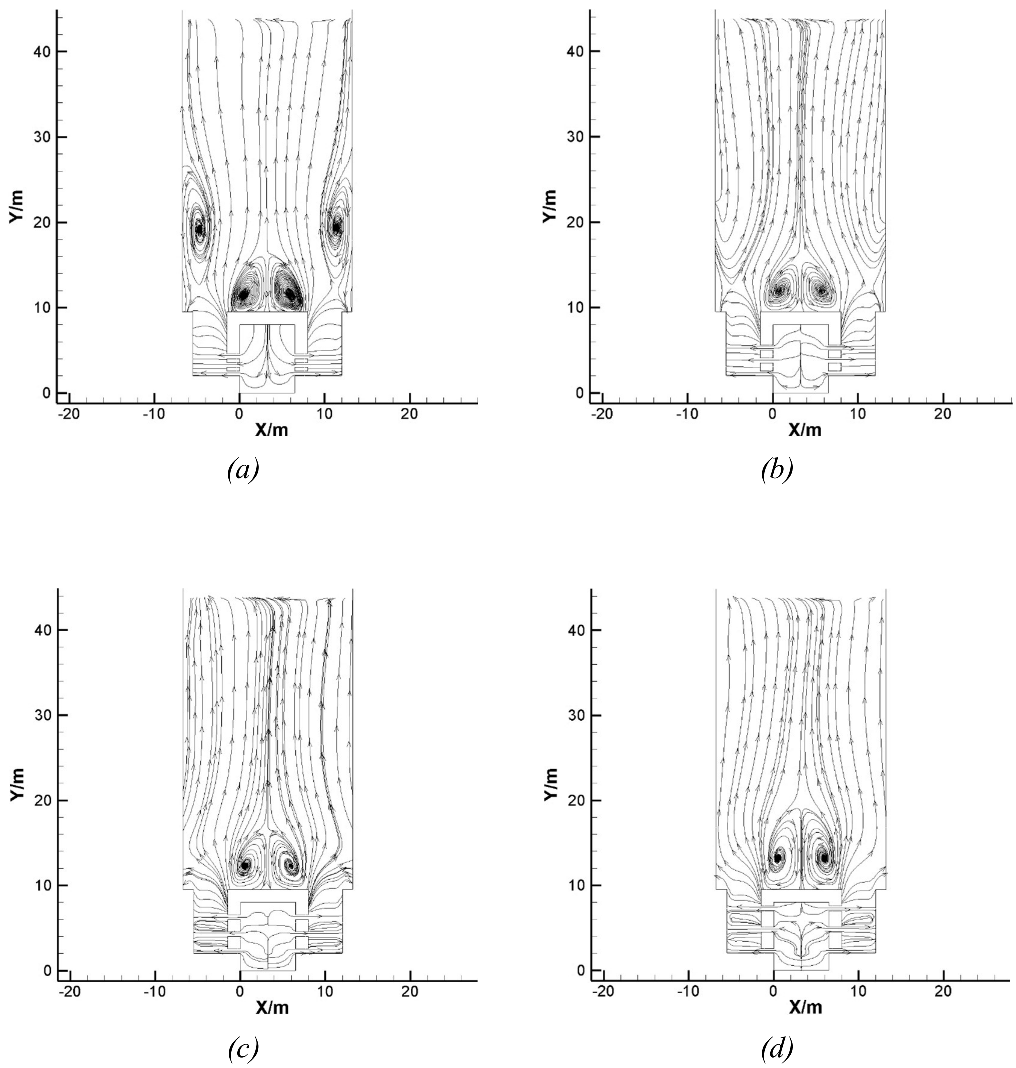


Figure 9. The streamline diagram of cross section (Z=-80.5m) for (a) CD1 (B/D=0.125), (b) CD2 (B/D=0.188), (c) CD3(B/D=0.25) and (d) CD4(B/D=0.313) at the time of maximum flow rate (T=410s), respectively. Z=-80.5m is the section at the central axis of the three-layer side ports in the middle of the lock chamber.

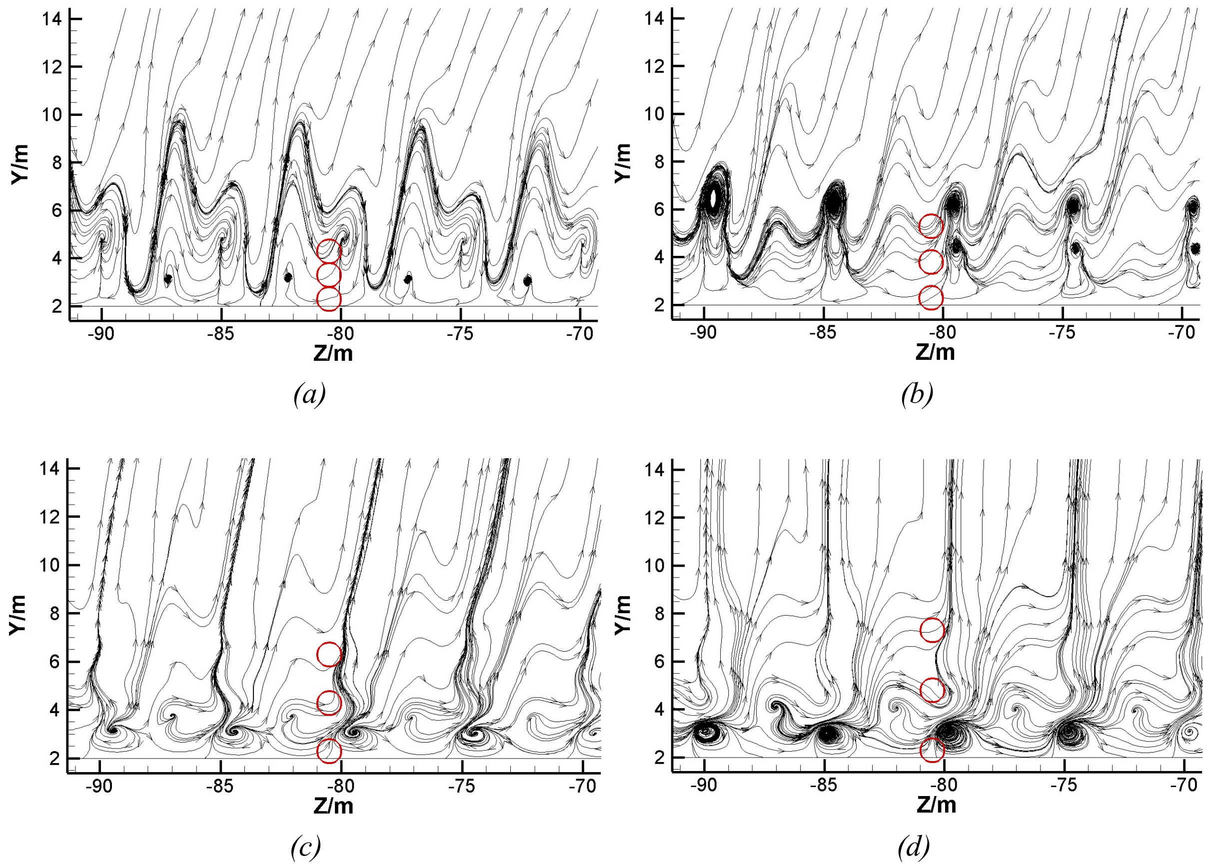


Figure 10. The streamline diagram of longitudinal section (X=10m) for (a) CD1 (B/D=0.125), (b) CD2 (B/D=0.188), (c) CD3 (B/D=0.25) and (d) CD4 (B/D=0.313) at the time of maximum flow rate (T=410s), respectively. X=10m is the section at the central axis of one side open ditch, and the side ports on the cross section are signed with a red circle.

3.3 Horizontal Velocity Contour Distribution

To further study the influence of different relative vertical spacing B/D on the energy dissipation performance in the open ditch. The horizontal velocity contour distribution in the horizontal section (Y=12.5m) of the lock chamber is presented in this section. As shown in Figure 11, at the time of the maximum flow rate (T=410s), the flow field on the horizontal section is greatly affected due to a large amount of water gushing from the open ditch, and the velocity gradient almost distributes wholly on the horizontal section of the lock chamber. The maximum velocities are 0.88m/s, 0.70m/s, 0.67m/s and 0.80m/s when the B/D=0.125(CD1), B/D=0.188(CD2), B/D=0.25(CD3) and B/D=0.313(CD4), respectively. It is interesting to see that the change tendency is consistent with that of the remaining specific energy and flow velocity distribution uniformity. According to the above analysis results, the maximum velocity in the horizontal section is found to be the smallest when B/D=0.25(CD3) compared with B/D=0.125(CD1), B/D=0.188(CD2) and B/D=0.313(CD4), indicating that the good energy dissipation performance is reached when B/D=0.25.

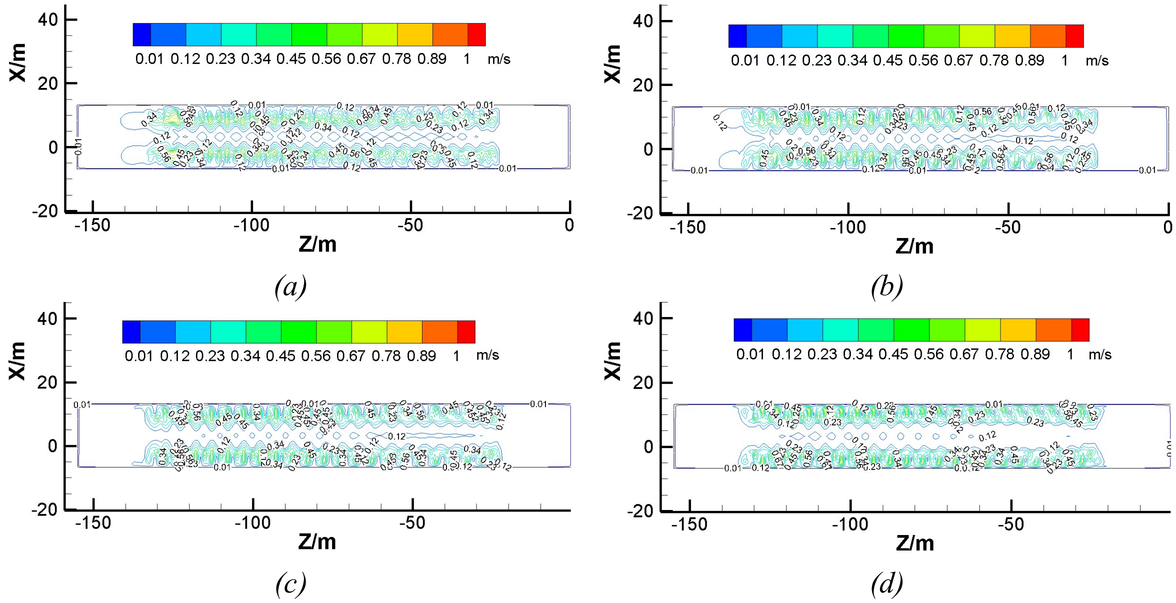


Figure 11. The diagram of velocity contour distribution on the horizontal section (Y=12.5m) for (a) CD1 (B/D=0.125), (b) CD2 (B/D=0.188), (c) CD3 (B/D=0.25) and (d) CD4 (B/D=0.313) at the time of maximum flow rate (T=410s), respectively. Y=12.5m is a horizontal section of a typical ship's draft bottom.

4 The energy dissipation mechanism analysis

The energy dissipation in the open ditch is essentially the transfer and conversion process of the water energy, that is, the water flows from the culvert through the side ports, and the jets are generated, then impinge the wall of the open ditch and a series of the energy-dissipation vortex is consequently formed in the open ditch. The water kinetic energy is dissipated due to the results of vortex shears and mixes. During the above process, the turbulent kinetic energy is an important parameter that reflects the energy dissipation performance. To study the characteristics of turbulent kinetic energy distribution in the open ditch, Figure 12 shows the corresponding distribution on the cross-section (*Z*=-80.5m) at the time of the maximum flow rate (*T*=410s). The results show that for *B/D*=0.125 and 0.188, the turbulent kinetic energy mainly exists in the middle and bottom of the open ditch due to the small energy dissipation space, resulting in the water energy insufficiently dissipated and a relatively large range of turbulent kinetic energy distributed above the open ditch, as shown in Figure 12(a) and (b). For *B/D*=0.25 and *B/D*=0.313, the maximum turbulent energy is mainly located near the outer wall of the open ditch, as shown in Figure 12(c) and (d). The mixing strength of the jet between the upper and lower two adjacent layers of the side port is weakened due to the excessive vertical spacing for *B/D*=0.313, resulting in a small turbulent kinetic energy between the two adjacent layers of the side ports. In conclusion, the distribution range of turbulent kinetic energy in the lock chamber tends to decrease with the increase of relative vertical spacing (0.125≤*B/D*≤0.313).

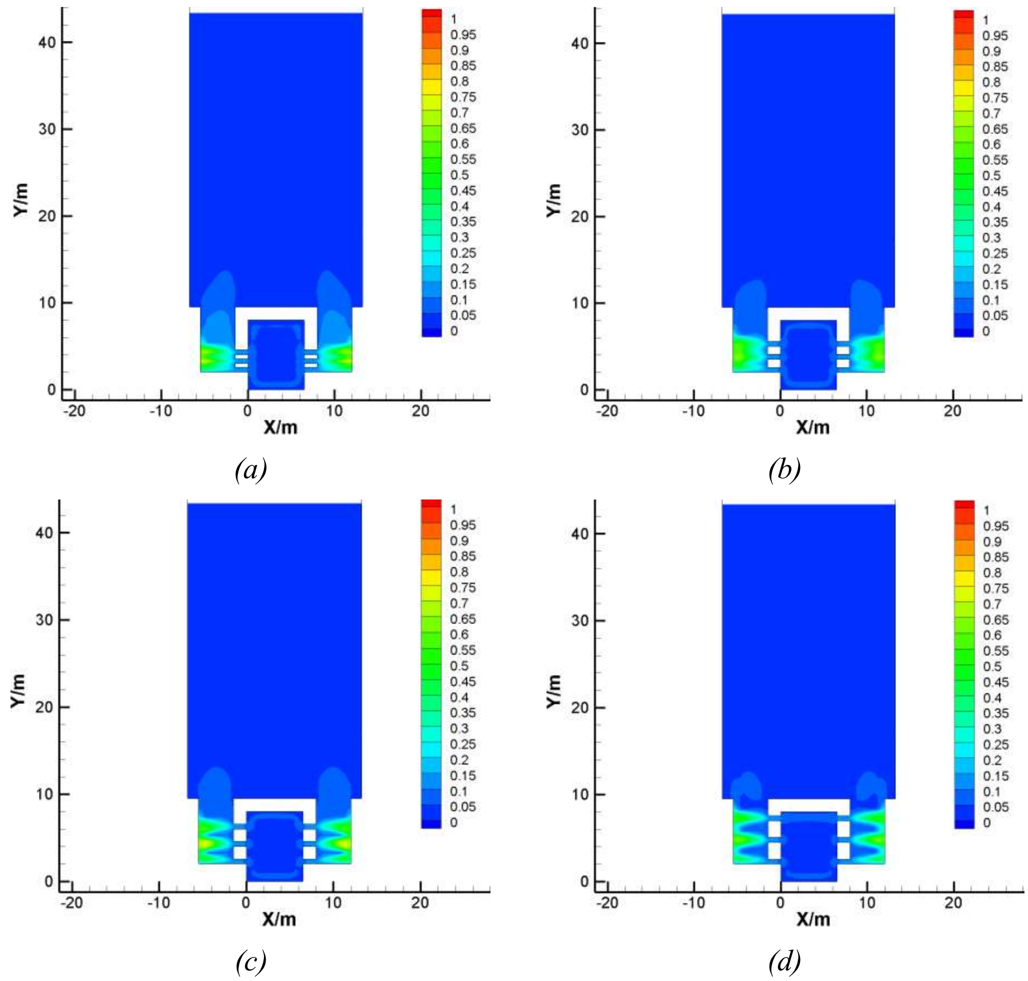


Figure 12. The diagram of distribution of turbulent kinetic energy on the cross section (Z=-80.5m) for (a) CD1(B/D=0.125), (b) CD2 (B/D=0.188), (c) CD3 (B/D=0.25) and (d) CD4 (B/D=0.313) at the time of maximum flow rate (T=410s). (All units in m^2/s^2).

5 The energy dissipation performance of different side port arrangements

To compare the energy dissipation performance of the three-layer side ports with those of single-layer and two-layer side ports, the remaining specific energy E_{pt} is selected for *B/D*=0.25(CD3), which is gained the good energy dissipation performance in this paper at the time of maximum remaining specific energy(*T*=310s) and maximum flow rate(*T*=410s). Of note, the generalized model and boundary condition in this paper are kept the same as the existing results [21]. Moreover, the single-layer and two-layer side ports arrangement cases Y1 and SC2, respectively, are also selected from the same literature. The corresponding results are shown in Figure 13.

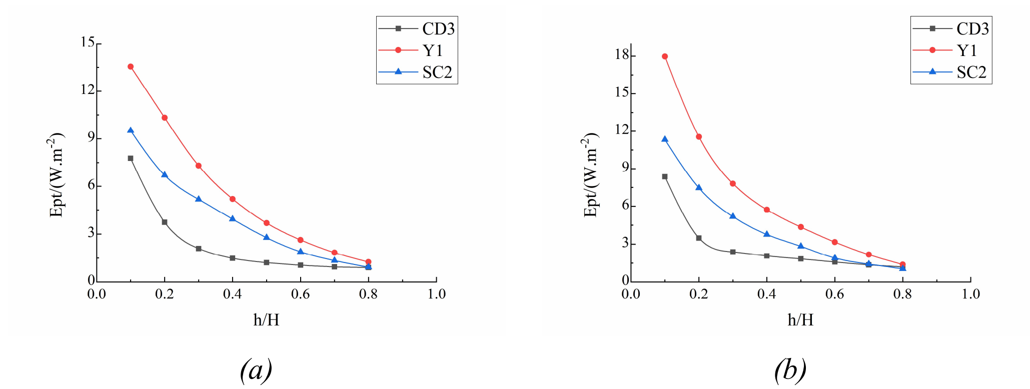


Figure 13. The remaining specific energy of three-layer side ports, two-layer side ports and single-layer side ports at (a) the time of maximum remaining specific energy (T=310s) and (b) the time of maximum flow rate (T=410s), respectively.

Under the same boundary conditions (e.g., the time history of filling flow rate, the side ports' cross-section area, etc.), Figure 13 shows that the profiles of the remaining specific energy of CD3 are lower than that of SC2. Similarly, SC2 is lower than Y1, indicating that the energy dissipation performance of three-layer side ports arrangement is better than that of two-layer and single-layer side ports arrangements. The reason is that the single-layer side ports only produce multiple jets in the longitudinal direction in the finite three-dimensional space, and these jets diffuse after impingement on the outer wall of the open ditch, shearing and mixing in the longitudinal direction, and then flow into the lock chamber. While the multi-layer side ports generate multi jets not only in the longitudinal direction but also in the vertical direction. After these jets impinge on the wall, shearing and mixing processes occur in longitudinal and vertical directions. In conclusion, compared with the single-layer and two-layer side ports arrangement, the best energy dissipation performance is found for the three-layer side ports arrangement.

6 Conclusions

(1) In this paper, the energy dissipation performance of the in-chamber longitudinal culvert with three-layer vertical aligning side ports and a single open ditch was presented by establishing the three-dimensional CFD model. The results showed that the energy dissipation performance was directly affected by the vertical spacing between side ports. When the vertical spacing B/D increased from 0.125 to 0.313, the energy dissipation performance first became better and then worse. The relatively good energy dissipation performance was reached when B/D=0.25.

(2) The energy dissipation mechanism was analyzed in terms of the distribution of turbulent kinetic energy within the lock chamber. The results showed that when the vertical spacing B/D increased from 0.125 to 0.313, the distribution range of turbulent kinetic energy in the lock chamber tended to decrease. When B/D increased to 0.313, the mixing strength of the jet between two adjacent layers of the side port was weakened due to the large vertical spacing between side ports.

(3) On the precondition of the same boundary conditions, the energy dissipation performance of single-layer, two-layer, and three-layer side ports arrangement (present design) were compared. The results showed that if all the side ports' cross-section area of each arrangement were kept the same, the energy dissipation performance of the present design was found to be the best due to multiple jets generated not only in the longitudinal but in the vertical direction, resulting in sufficient mixing processes.

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