Numerical simulation on geometrical parameters for closed sump

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Abstract. The closed sump is a typical inlet passage of middle and small pumping station. It has the characteristics of low channel height, small foundation excavation depth, simple structure, a single cross sectional shape changes, ease of construction and other features, so more and more attention and application has been paying on this closed sump in pumping station project. However the flowing pattern within the closed sump is complex, the design is not perfect in some respects, the structure size does not be optimized. Based on the background for renewal and transformation of a pumping station, according to the three-dimensional incompressible fluid Reynolds-averaged N-S equations, the RNG k-e model, the CFD technology. The study on the draught in closed sump might reduce the length of pump shaft to enhance the stability of the pump unit operation. The results reveal the effect of the change of the height of plate. The turbulence in back wall might cause vortex when the height is high. The height of plate had be recommended control in 0.65D-0.85D.The better parameter combination of geometry of closed sump had be given through comparing the results of the orthogonal test and the comprehensive test. The floor clearance should be control in 1.0D. (D is the diameter of flared pipe)

Introduction

The closed sump comes from the open sump with a plate. It have double features of traditional sump and inlet conduit due to the quartet geometric shape and the environment with pressure. So by comparison, it has the unique characteristics of low channel height, small foundation excavation depth, simple structure, a single cross sectional shape changes, ease of construction and other features [1~5], so more and more attention and application has been focused on this closed sump at pumping station project [6~10].

Jiangang Feng [10] put forward that the design of intake sump should make flow smooth-going, no harmful vortex in order to ensure the safe operation of the pump unit. Songshan Chen [11] designed five different suction open height to observe the inlet flow pattern. Charles [12] put forward the velocity in sump should be control near 0.3m/s. Iverson [13] gave the value range of draught for high specific speed pump. Matahel Ansar [14] for the flow pattern in rectangular sump in some inlet conditions. For eliminate vortex bell attached under the bottom, the experiments also designed some vortex suppression program of separator. Flow pattern of the closed sump and hydraulic performance of five different

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heights of the closed sump had be analyzed orthogonal test had be set to study the geometrical parameters of the closed pump.

1.1 Mathematical Model

Calculations are performed using the commercial code CFX®. The numerical model is based on the Reynolds-Averaged Navier-Stokes (RANS) equations with the RNG k-ε model to calculate the Reynolds stresses. First-order upwind discretizations are used for the convective terms and turbulent kinetic energy and dissipation, while a second-order central differencing scheme is used for the diffusive terms. The temporal discretization is second-order implicit. The SIMPLE algorithm is used for the pressure-velocity coupling.

Sliding interfaces up- and downstream of the impeller allow the impeller to rotate with respect to the inlet and stator. The flow in the impeller is solved in the rotating frame of reference. To this end the apparent Coriolis and centrifugal forces are added to the RANS equations as source terms.

Two basic calculation methods are adopted. The first one is a quasi-steady approach in which the flow is assumed steady in its corresponding reference frame. In this multiple reference frame (MRF) method, the transient effect of the rotor-stator interaction is neglected. The convergence criterion for all equations is set to 10^{-4}. A solution normally serves as a good initial solution for the second, truly unsteady, moving mesh method. In this method, the connections between rotating and stationary part are updated each time step. The transient solution is monitored as time progresses until the solution becomes periodic at blade passing frequency.

1.2 numerical simulation

The numerical domain consists of the inlet and outlet passages, the axial flow impeller with three blades and the diffuser with seven vanes. Inflow and outflow boundaries are located sufficiently far away from the pump not to influence the flow characteristics. The extent of the domain in upstream direction is especially important to allow for inlet flow recirculation at part load. Another important part is the tip clearance gap between the impeller blades and the casing. A number of layers of cells are placed in this region to allow for leakage flow over the blade tips.

Using an extrusion method, an O-type grid of hexagonal cells is created around the impeller and stator blades to ensure good mesh quality in terms of size and skewness. Because of the complex topology of the pump, the interior of the domain is filled with an unstructured mesh of tetrahedral cells.

A mesh-sensitivity study was carried out to assess the required mesh density. Several grids were considered, ranging from a total number of cells of 2×10^5 up to 2×10^6, where care was taken that y^+ values at the solid boundaries remained favorable. No further convergence was obtained for grids with more than 1.5×10^6 cells.

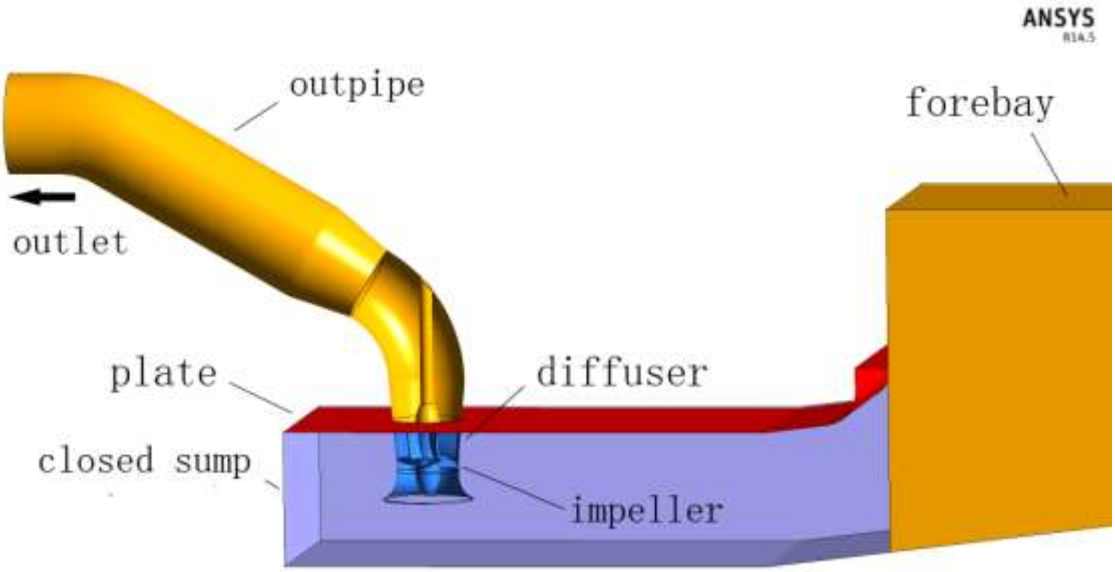


Figure.1 Computational Domain

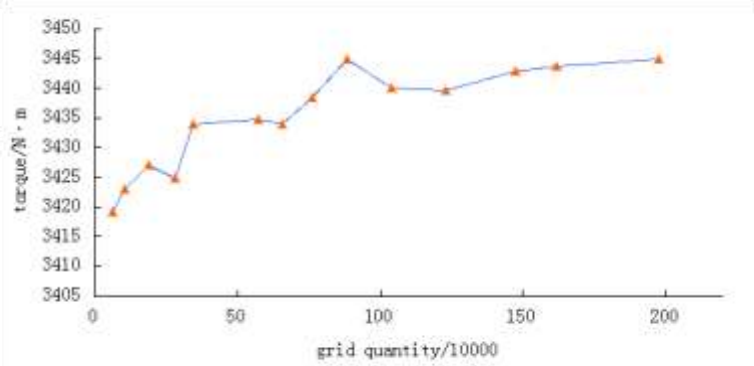


Figure.2 Independence of Grid

The inlet boundary condition is specified as a uniform velocity whereas at the outlet an outflow boundary condition is applied which allows for non-uniformity in both velocity and pressure. No-slip boundary conditions and wall functions are used for the solid walls.

2. Calculation Results

The geometric parameters of sump are shown in Fig3.

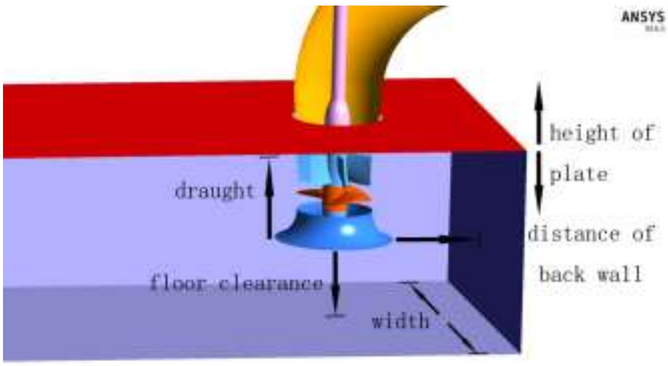


Figure.3 Geometric Parameters of Sump

2.1. Height of Plate

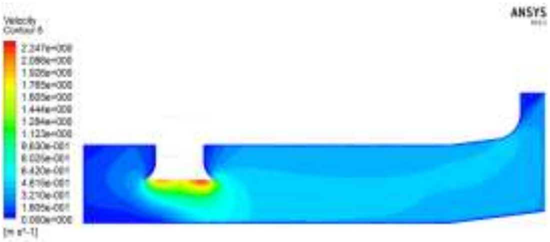
The closed sump came from the open sump with a plate. The plate changed the flowing law in the sump. So a research about the height of the plate had be taken first. In order to reduce the influence of other geometry parameters, larger geometry parameters of the sump had be set. The calculation schemes are shown in Table 1.Five different heights of plate had be set to analyze the changes of hydraulic performance.

Table 1. Calculation Schemes

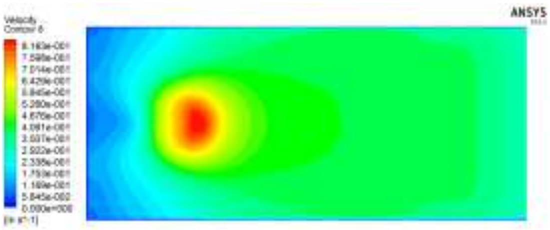
NO.	Width	Distance of Back Wall	Floor Clearance	Height of Plate
1	3 D	0.82 D	0.7 D	2.05 D
2				1.26 D
3				1.05 D
4				0.85 D
5				0.65 D
6				0.46 D

Fig.4 shown the distribution of the velocity of the center vertical cross-section and the horizontal cross-section on five heights of plate. On the center section, the height of the area of low velocity increased as the plate height increases. When the plate height is 1.26D, the area of low velocity spread all over the back wall. On the horizontal section, the area of low velocity slightly expended from 0.46D to 0.85D, and the distribution of velocity was uniform. From 1.05D to 1.26D, the flow pattern became turbulence.

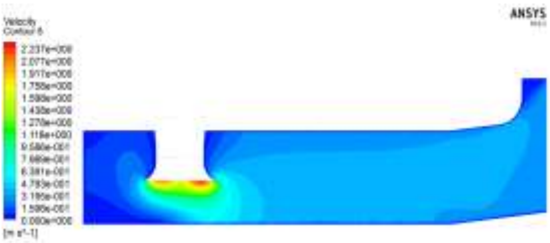
The uniformity of velocity and the variety average angle of velocity had be analysed. The uniformity of velocity would get better when the height is 0.65D-0.85D.Also the uniformity of velocity is good in the open sump which the height is 2.05D.When the height is 0.65D-0.85D the average angle of velocity is better. The height of plate should be control in 0.65D-0.85D had be recommend.



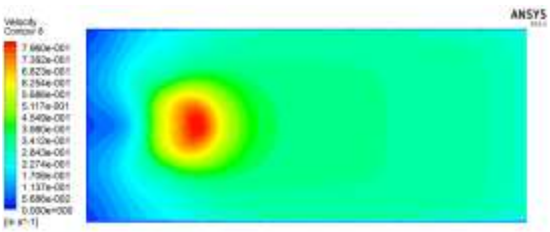
(a)Velocity of Vertical Cross-Section on 0.46D



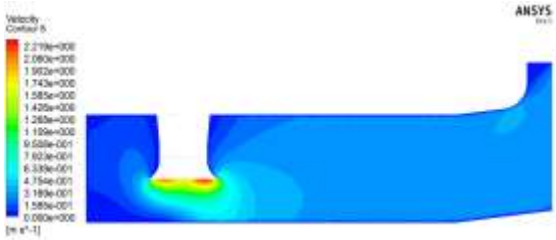
(b)Velocity of Horizontal Cross-Section on 0.46D



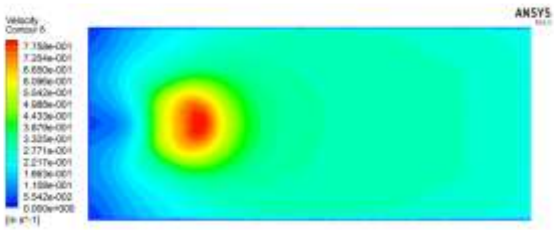
(c)Velocity of Vertical Cross-Section on 0.65D



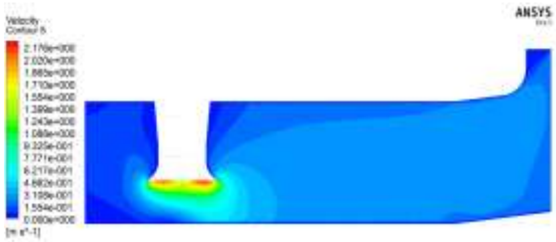
(d)Velocity of Horizontal Cross-Section on 0.65D



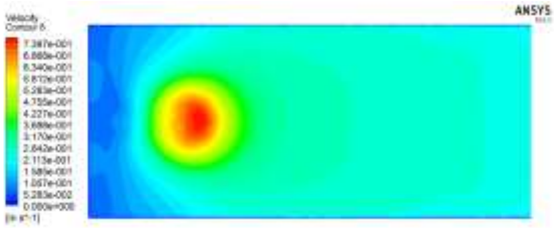
(e)Velocity of Vertical Cross-Section on 0.85D



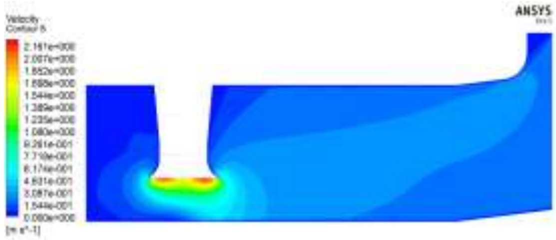
(f)Velocity of Horizontal Cross-Section on 0.85D



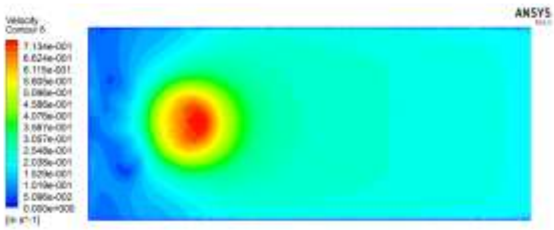
(g)Velocity of Vertical Cross-Section on 1.05D



(h)Velocity of Horizontal Cross-Section on 1.05D



(i)Velocity of Vertical Cross-Section on 1.26D



(j)Velocity of Horizontal Cross-Section on 1.26D

Figure.4 Cloud Image of Velocity on Section of Five Heights

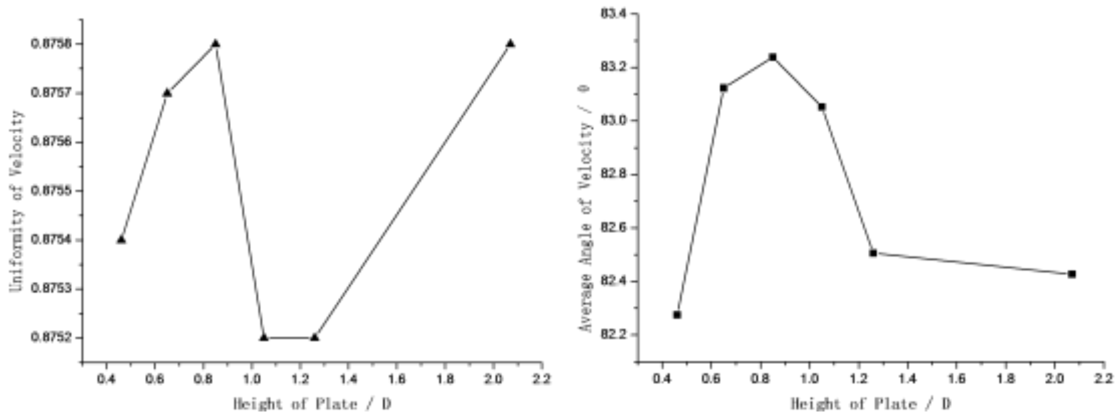


Figure.5 Uniformity of Velocity and Average Angle of Velocity

2.2. Orthogonal Test on Geometrical Parameters

2.2.1 Design of Orthogonal Test Four Geometrical Parameters were chose as the factors for the test. They are width, distance of back wall, floor clearance and draught. Four levels were set in every factor.

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The L16 (4^4) table was selected in the test. Otherwise, the pump assembly efficiency, the uniformity of velocity and the average angle of velocity were selected as the index of test.

Table 2. Factors and Levels

Levels	Factors			
	A (Height of Plate)	B (Distance of Back Wall)	C (Floor Clearance)	D (Width)
1	0.46 D	0.4 D	0.4 D	2.25 D
2	0.65 D	0.6 D	0.6 D	2.5 D
3	0.85 D	0.8 D	0.8 D	2.75 D
4	1.05 D	1.0 D	1.0 D	3.0 D

Table 3. Factors and Levels

No.	Factors				Geometrical Parameters			
	A	B	C	D	Height of Plate	Distance of Back Wall	Floor Clearance	Width
1	1	1	1	1	0.45 D	0.4 D	0.4 D	2.25 D
2	1	2	2	2	0.45 D	0.6 D	0.6 D	2.5 D
3	1	3	3	3	0.45 D	0.8 D	0.8 D	2.75 D
4	1	4	4	4	0.45 D	1.0 D	1.0 D	3.0 D
5	2	1	2	3	0.65 D	0.4 D	0.6 D	2.75 D
6	2	2	1	4	0.65 D	0.6 D	0.4 D	3.0 D
7	2	3	4	1	0.65 D	0.8 D	1.0 D	2.25 D
8	2	4	3	2	0.65 D	1.0 D	0.8 D	2.5 D
9	3	1	3	4	0.85 D	0.4 D	0.8 D	3.0 D
10	3	2	4	3	0.85 D	0.6 D	1.0 D	2.75 D
11	3	3	1	2	0.85 D	0.8 D	0.4 D	2.5 D
12	3	4	2	1	0.85 D	1.0 D	0.6 D	2.25 D
13	4	1	4	2	1.05 D	0.4 D	1.0 D	2.5 D
14	4	2	3	1	1.05 D	0.6 D	0.8 D	2.25 D
15	4	3	2	4	1.05 D	0.8 D	0.6 D	3.0 D
16	4	4	1	3	1.05 D	1.0 D	0.4 D	2.75 D

2.2.2 Test Results K_i represents the sum of the test results in every rank when the level is i. $k_i = K_i / s$, s is the quantity of levels. R is range, $R = \max\{K_1, K_2, K_3, K_4\} - \min\{K_1, K_2, K_3, K_4\}$ in every rank。

There are two preferable schemes in the table which are preferable scheme in test and preferable scheme in theoretical analysis. Preferable scheme in test is the preferable parameter combination in this orthogonal test. Preferable scheme in theoretical analysis is the parameter combination which was analyzed through observing the K_i. In pump sets, pump assembly efficiency, uniformity of velocity and average angle of velocity are the index which were bigger is better. So the preferable scheme in theoretical analysis comes from the level which the K is largest. However the preferable scheme in theoretical analysis is not in the orthogonal test which reflected the superiority of the orthogonal test.

Table 4. Test Results

No	Factors				Test Results		
	A	B	C	D	Pump Assembly Efficiency $\eta/\%$	Uniformity of Velocity $\overline{V_u}/\%$	Average Angle of Velocity $\overline{\theta}$
1	1	1	1	1	73.582	87.02	81.3533
2	1	2	2	2	75.449	87.40	83.2057
3	1	3	3	3	75.701	87.60	83.0590
4	1	4	4	4	75.555	87.31	82.1576
5	2	1	2	3	75.396	87.42	83.4115
6	2	2	1	4	74.649	87.33	82.9470
7	2	3	4	1	76.274	87.57	83.4570
8	2	4	3	2	75.284	87.60	83.1019
9	3	1	3	4	75.687	87.54	83.1748
10	3	2	4	3	76.227	87.53	83.6540
11	3	3	1	2	74.164	87.26	82.1396
12	3	4	2	1	75.307	87.45	82.6834
13	4	1	4	2	76.270	87.52	83.6521
14	4	2	3	1	74.861	87.34	81.6463
15	4	3	2	4	75.010	87.48	82.9840
16	4	4	1	3	74.536	87.36	82.6940

Table 5. Anlysis of Results

Index		A	B	C	D
Pump Assembly Efficiency $\eta/\%$	K_1	300.287	300.935	296.931	300.024
	K_2	301.603	301.186	301.162	301.167
	K_3	301.385	301.149	301.533	301.86
	K_4	300.677	300.682	304.326	300.901
	k_1	75.07175	75.23375	74.23275	75.006
	k_2	75.40075	75.2965	75.2905	75.29175
	k_3	75.34625	75.28725	75.38325	75.465
	k_4	75.16925	75.1705	76.0815	75.22525

	Range R	1.316	0.504	7.395	1.836
	Primary-Secondary	C A D B			
	Preferable Scheme in Test	$A_2B_3C_4D_1$ or $A_4B_1C_4D_2$			
	Preferable Scheme in Theoretical Analysis	$A_2B_2C_4D_3$			
Uniformity of Velocity $\overline{V}_u$ / %	K_1	349.33	349.5	348.97	349.38
	K_2	349.92	349.6	349.75	349.78
	K_3	349.78	349.91	350.08	349.91
	K_4	349.7	349.72	349.93	349.66
	k_1	87.3325	87.375	87.2425	87.345
	k_2	87.48	87.4	87.4375	87.445
	k_3	87.445	87.4775	87.52	87.4775
	k_4	87.425	87.43	87.4825	87.415
	Range R	0.59	0.41	0.33	0.53
	Primary-Secondary	A D B C			
	Preferable Scheme in Test	$A_1B_3C_3D_3$ or $A_2B_4C_3D_2$			
	Preferable Scheme in Theoretical Analysis	$A_2B_3C_3D_3$			
Average Angle of Velocity $\overline{\theta}$	K_1	329.7756	331.5917	329.1339	329.14
	K_2	332.9174	331.453	332.2846	332.0993
	K_3	331.6518	331.6396	330.982	332.8185
	K_4	330.9764	330.6369	332.9207	331.2634
	k_1	82.4439	82.897925	82.283475	82.285
	k_2	83.22935	82.86325	83.07115	83.024825
	k_3	82.91295	82.9099	82.7455	83.204625
	k_4	82.7441	82.659225	83.230175	82.81585
	Range R	3.1418	1.0027	3.7868	3.6785
	Primary-Secondary	C D A B			
	Preferable Scheme in Test	$A_3B_2C_4D_3$ or $A_4B_1C_4D_2$			
	Preferable Scheme in Theoretical Analysis	$A_2B_3C_4D_3$			

Interaction might exist in factors. One factor changed may change the influence of other factors. So the preferable scheme in theoretical analysis should be verified. If the results are better than the preferable scheme in test, the preferable scheme in theoretical analysis should be the better scheme. Otherwise the preferable scheme in test might be the better scheme.

2.2.3 Comprehensive test The table given three preferable schemes in theoretical analysis is $A_2B_2C_4D_3$, $A_2B_3C_3D_3$ and $A_2B_3C_4D_3$.A_2 and D_3 is the better level in the three schemes. B and C have two better levels. So a 2×2 comprehensive test was designed to verify the results which shown in Table 6.

Table 6. 2×2 Comprehensive Test Results

Preferable Scheme in Theoretical Analysis	Pump Assembly Efficiency η/%	Uniformity of Velocity $\overline{V}_u$/%	Average Angle of Velocity $\overline{\theta}$
$A_2B_2C_4D_3$	0.761619568	87.49	83.116
$A_2B_2C_3D_3$	0.756011045	87.51	83.2975
$A_2B_3C_3D_3$	0.755241291	87.54	83.0813
$A_2B_3C_4D_3$	0.763619693	87.52	83.4524

The better parameter combination had be given in Table 7. Through comparing the results of the orthogonal test and the comprehensive test. The floor clearance should be control in 1.0D.

Table 7. The Better Parameter Combination

The Better Parameter Combination	Height of Plate	Distance of Back Wall	Floor Clearance	Width
$A_2B_3C_4D_3$	0.65 D	0.8 D	1.0 D	2.75 D
$A_2B_3C_4D_1$	0.65 D	0.8 D	1.0 D	2.25 D
$A_3B_2C_4D_3$	0.85 D	0.6 D	1.0 D	2.75 D
$A_4B_1C_4D_2$	1.05 D	0.4 D	1.0 D	2.5 D

3. Conclusion

Based on the three-dimensional numerical simulation, the effect of the height of plate and the effect of all geometrical parameters were studied. The research results can be applied in the similar closed sump of pumping stations.

The hydraulic performance would be better when the height of plate is lower. The height of plate should be controlled in 0.65D-0.85D.

The better parameter combination of geometry of closed sump had be given through comparing the results of the orthogonal test and the comprehensive test. The floor clearance should be controlled in 1.0D.

Acknowledgments

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Reference

[1] Liu C 2009 *Pump and pumping station* [M].Beijing: China Water Power Press.

[2] Liu C, Ma C S 1994 Experiment and research on improvement measures of forebay flow pattern of pumping stations [J].*Journal of Institute of Architecture (Natural Sciences)*, **2(1)**:9~12.

[3] Cheng L, Liu C, Zhou J R, et al. 2005 Numerical simulation of turbulent flow around sill with RNG k-ε turbulent model[J].*Transactions of the Chinese Society for Agricultural Machinery*,**36(3)**:37~39.

[4] Choi J W, Choi Y D, Kim C G 2010 Flow uniformity in a multi-intake pump sump model. The University of lowa, *Journal of Mechanical Science and Technology*, **24 (7)**:1389~1400.

[5] Gaston E F, Marcela P, Larry W 2009 Numerical simulation of free surface flows on a fish bypass [J]. *Computers& Fluids*, **38(5)**: 997- 1002.

[6] Cai F L, Zhang Z M 2000 Study on guide piers in flank inlet-outlet with double flow directions [J].*Journal Of Hohai University*, **28(2)**:74~77.

[7] Zhou L C 2010 Numerical analysis on improvement of flow conditions in forebay of pumping station by setting separation piers [J]. *Journal of Yangtze River Scientific Research Institute*, **27(2)**:31~33.

[8] Liu C, Han X, Zhou J R, et al. 2009 Numerical simulation of turbulent flow in forebay with side-intake of pumping station [J]. *Drainage and Irrigation Machinery*, **27(5)**:281~286.

[9] Liu C, Cheng L, Tang F P 2001 Numerical simulation of three-dimensional turbulent flow inside a pumping forebay [J]. *Transactions of the Chinese Society of Agricultural Machinery*, **32 (6)**:41~44.

[10] Zhou J R, Liu C, Tang F P 1996 Simulation on the flow pattern in diffusion channel of large pumping station [J]. *Water Resource and Hydropower Engineering*, **1996(9)**:41~43.

[11] Chen S S, Ge Q, Yang G P 2004 The experiment on pump setting characterisics with different open height [J]. *Journal of Yangzhou University (Natural Science Edition)*, **7(3)**:59~62.

[12] Sween C E, Rex A E, Duncan H 1982 Pump sump design experience [J], *J.of Hydraulic Divisin*, **108(3)**:361-377

[13] Iversen H W 1953 Berkeley,Calif. Studies of Submergence Requirements of High-Specific-Speed Pumps [J]. *The American Society*, **1953(75)**:635-641

[14] Matahel A, Tatsuaki N 2001 Experimental study of 3D pump-intake flows with and without cross flow [J]. *Journal of Hydraulic Engineering*, **127(10)**:825-834