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Performance Prediction and Experiment Study on Axial Pump Station Device

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Abstract: Axial pump station devices were widely used in various fields of the national economy, especially in water conservancy projects. But because of complicated flow, the design and manufacture processes were very complex and the economic performance was poor. This article's study aim was to predict the performance and master the essential performance curves of axial pump and pump station device. One of the research's final aim was to short the cycle of axial pump's design, manufacture and renovation. The second was to improve the economic performance of axial pump and pump station device. In this article, mathematic models of performance prediction were built based on hydraulic loss method and the structure parameters of pump and pump station device. Then, the application program was developed. The essential performance curves could be drawn and the performance could be predicted according with the program. At the same time, site tests were carried out in Tianshan grade 1 pump station. Checking by contrast analysis of actual measured data and predicted data, the performance prediction models and application program were practical and played an important role in the process of technical reform. Thus, technical reform time were shorten, larger economic and social benefits were obtained. In summary, the predicted data was credible, the predicted model and application program was practical. But the predicted accuracy should be improve and the practicability should be expand further. So, the further operations were expected at end of the study.

Key words: Hydraulic loss, axial pump station device, performance prediction, mathematic model, essential performance curves, experiment study

INTRODUCTION

Water conservancy is the foundation of the national economy. Pump station is the important section of water conservancy project and is the key to protect and devel-op grain production. Compared to other water conserva-ncy projects, it plays an irreplaceable role to solve the three water resource issues today, such as flood, water shortage and deterioration of water environment. To improve the efficiency of pump station is the most basic question in the process of design, technical reform and operation and also this is unified with the national sustainable development strategy. Chinese electromecha-nical drainage and irrigation industry started late, thus many questions exist, for example: Low efficiency of pu-mp device, exceeding standard of unit energy consump-tion , reduction of project benefits, abates of anti-disaster ability and so on.

The actual flow in axial pump is so complex that the rules were not be understanded clearly. So far, the design of axial pump is at the stage of half theory and half experience. Generally, manufactures adopt the proc-ess containing design, trial-produce, experiment and improving. The process is cockamamie and the consum-ptions of manpower, financial resources and times are massive. According with the pipe parameters of axial pump station and the structure parameters of axial pump, if the sundry performances can be predicted and the primary performance curves can be mastered, not only the interrelated costs can be reduced significantly but also the cycle of design, manufacture and renovation can be shorten availably and huge social and economic benefits can be produced at the same time.Therefore, researchers have a long pursuit goal to gain the complete performance curves economically and reliably (He *et al*., 2003). Now, the complete performance curves could be acquired through model experiment and transform calculation. Several important curves also could be obtained through performance transform calculation based on existed data. The curves gained by the former method were true and reliable but the experiment costs were very expensive and the period was very long. The latter could reduce experiments but the predicted accuracy could be ensured only in the vicinity of the known data points, due to the over reliance on the accuracy and the satisfied degree of similarity assumpti-on.

Qian Xiao's research was about the mixed-flow pump comparison with predicted and actual efficiency, indicated

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that the predicted method was simple and practical (Qian *et al*., 1999). Liu Guan-lin predicted the complete characteristics of pump by using BP neural network and got the reliable conclusion on prediction (Liu *et al*., 2000). Wang Guo-yu discussed the numerical simulation of 3-D turbulent flow and performance predi-ction of a pump turbine runner (Wang *et al*., 2001). The result showed that the method was suitable for the performance and flow field analysis at the runner design stage (Liu *et al*., 2000). Tan Ming-gao expounded the predicted theory of centrifugal pump and develope the program to predict the performance in his master's dissertation. He proved that the prediction theory was correct and the software was practical (Tan, 2006). Ge Qiang studied water conservancy characteristic conversion and performance prediction for low-left pumping station in his doctor's dissertation. He predicted the characteristics of pump station successfully and gave some reasonable advice for lager pump station in stable operation (Ge, 2006). In summary, the previous research focused on the centrifugal pump and mixed-flow pump. But the study on axial pump was few. The author's team took hard work on axial pump and gained some achievements.

So far, there are three methods on performance prediction: Hydraulic loss method, neural network meth-od and flow field analysis method. In this article, the research was based on the hydraulic loss method.

METHODOLOGY

The first step of hydraulic loss method is to analyze the physical essence and influence factor of hydraulic loss. The second is to seek the relation between the loss and pump structure parameter and the last is to build the mathematic mode of hydraulic loss. Thus the performan-ce parameters could be predicted and the essential performance curves could be gained. So the method key and base are the analysis and calculation. And the aim functi-on is the comprehensive performance of pump station device. Because of the whole consideration of various factor's effect in pump, the hydraulic loss method has practicality and accuracy. So it is the common method to predict the pump's performance currently.

MATHEMATIC MODE

Loss and efficiency of pump: During the operation of axial flow pump, there are three types of loss: Mechanical loss, volume loss and hydraulic loss. The last one accounted for the largest proportion of loss and was the definitive factor to influence the pump efficiency. According to literature (He and Guo, 2008), the expressions of mechanical efficiency η_m and volume efficiency η_v were given below:

$$\left.\begin{aligned}\eta_m &= (P-\Delta P_m)\times 100\%/P\\ \eta_v &= (Q_T-q)\times 100\%/Q_T\end{aligned}\right\} \quad (1)$$

In the last written, mechanical loss ΔP_m was about 3-15% of pump shaft power P and leakage q was about 4-10% theoretical flow Q_T.

The theoretical head of finite number lamina pump can be denoted by H_T, then the expression of power loss caused by the flow leakage was as follow:

$$\Delta P_v = \rho g q H_T \quad (2)$$

According to massive references, hydraulic loss occurred mainly in the suction chamber, impeller channel and casing of axial flow pump. The detailed accounts follow:

- The suction chamber loss mainly includes local loss and friction loss. But the figure of friction loss was very small, especially at the design condition. Based on literature (Chen and Wu, 2003), the expression of local loss was as follow:

$$\Delta h_x = k_x v_0^2/2g \quad (3)$$

In the equation, k_x was the hydraulic loss coeffic- ient of the suction chamber and v_0 was the velocity of pump in the suction chamber inlet.

- The loss in impeller channel mainly includes impact loss at the entrance, friction loss, divergence loss and hydraulic loss at the export (Liu, 2001). In most cases, using the semi-empirical and semi-theory formula to calculate the loss

Owing to the changes of operating conditions, rate of flow Q deflected design flow Q_d, the entrance f-low angle β_1 was not equal to the entrance blade inci-dence β_{1a}, so the impact loss occurred. The entrance impact loss of impeller could be expressed as:

$$\Delta h_1 = k_1 w_1^2/2\,g \quad (4)$$

In the above formula, k_1 was the impeller entran-ce impact loss coefficient and w_1 was the opposite v-elocity at impeller entrance which could be solved based on the fluid flow in axial pump meet the cylindrical layer independence hypothesis.

According with the number of impeller and the structure size of channel, the friction loss in impeller channel Δh_2 could be calculated by the next formula:

$$\Delta h_2 = zk_2\lambda(l_a / D_a)(w_a^2 / 2g) \quad (5)$$

In the last written, z was the number of impeller, k_2 was the channel friction loss revise coefficient, λ was the on-way friction coefficient, l_a was the channel length, D_a was the average diameter of channel and w_a was the average opposite velocity of fluid in channel.

The parameters in Eq. 5 formula could be calculated by the following expressions:

$$\left.\begin{aligned} D_a &= (D_2 + D_1)/2 \\ \lambda &= [1.74 + 21g(D_a/2\delta)]^{-2} \\ w_a &= (w_1 + w_2)/2 \\ l_a &= (D_2 - D_1)/(\sin\beta_{2a} + \sin\beta_{1a}) \end{aligned}\right\} \quad (6)$$

In the above formulas, D_1 was the impeller entrance diameter, D_2 was the impeller export diameter, δ was the impeller surface roughness, w_2 was the impeller export opposite velocity and β_{2a} was the export blade incidence.

Based on the absolute value of square difference about w_1 (the impeller entrance opposite velocity) and w_2 (the impeller export opposite velocity), Δ_{h3} (local loss in impeller) could be solved as follow:

$$\Delta h_3 = k_3\left|w_1^2 - w_2^2\right| / 2g \quad (7)$$

The hydraulic loss at impeller export Δ_{h4} was re lated to the circumferential velocity v_{2u} and axial velo city v_{2m} of fluid at the impeller export which could be solved as follow:

$$\Delta h_4 = k_4(v_{2m}^2 + v_{2u}^2) / 2g \quad (8)$$

So, the total hydraulic loss in axial pump impeller Δ_{hl} could be expressed as follow:

$$\Delta h_l = \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 \quad (9)$$

- Hydraulic loss of chamber pressure mainly includes local loss and on-way friction loss. The common formula to calculate on-way friction loss was:

$$\Delta h_5 = fLQ^m / D^b \quad (10)$$

In the equation, f was the friction resistance coefficient, L was the length of outlet pipeline, D was the overage diameter of discharge elbow, b was the pipe diameter index and m was the flow index. According to literature (Qiu, 2001), the number of f, m and b could be detected.

The common formula to calculate local loss was:

$$\Delta h_6 = \zeta v^2 / 2g \quad (11)$$

In the last written, ζ was the local resistance coefficient of discharge elbow and v was the average velocity of discharge elbow. Based on literature (Qiu, 2001), ζ and v could be solved.

So, the total hydraulic loss in chamber pressure Δ_{hy} was:

$$\Delta h_y = \Delta h_5 + \Delta h_6 \quad (12)$$

From (a), (b) and (c), it could be seen that the total hydraulic loss in axial pump Δh was:

$$\Delta h = \Delta h_x + \Delta h_l + \Delta h_y \quad (13)$$

Then the power loss caused by the hydraulic loss ΔP_h was:

$$\Delta P_h = \rho g(Q_T - q)\Delta h \quad (14)$$

Therefore, hydraulic efficiency of axial pump η_h was the ratio of actual and theoretical head, that was:

$$\eta_h = H|H_T = H|(H+\Delta h) \quad (15)$$

In summary, the power loss ΔP and the overall efficiency η of axial pump were given below:

$$\left.\begin{aligned} \Delta P &= \Delta P_m + \Delta P_v + \Delta P_h \\ \eta &= P_e / P = \eta_h\eta_v\eta_m \end{aligned}\right\} \quad (16)$$

In the equation, P_e was the effective efficiency of pump, that meaned the actual gained power of fluid and the number was ρgQH.

Based on literature (Tan, 2006; Zhang *et al*., 1996; Guo and Wang, 1983; Yang, 2001; Wang *et al*., 1997), it could be initially confirmed the number of various loss correction coefficient, such as k_x, k_1, k_2, k_3 and k_4.

Pipeline loss and efficiency: The energy suppled from pump station, not only needs to raise the water to the requisite height and pressure but also needs to overcome various resistance of pipeline. Therefore, the pipeline head loss should be calculated (Qiu, 2004). Generally, pipeline loss mainly includes on-way friction loss and local loss.

On-way friction loss Δh_f and local loss Δh_j could be calculated by the general formula of friction loss and local loss, that were:

$$\left.\begin{aligned}\Delta h_f &= flQ^m/D^b\\ \Delta h_j &= \Sigma\zeta_i v_i^2/2g\end{aligned}\right\} \qquad (17)$$

In the above equation, ζ_i was the local resistance coefficient of the i section of pipeline which can be solved based on literature (Qiu, 2001; Qiu, 2004) and v_i was the average velocity of the i section of pipeline.

Therefore, pipeline loss Δh_p and power loss ΔP_p were:

$$\left.\begin{aligned}\Delta h_p &= \Delta h_f + \Delta h_j\\ \Delta P_p &= \rho g Q \Delta h_p\end{aligned}\right\} \qquad (18)$$

Generally, the loss flow of pipeline was negligible (Luan, 1993), so the pipeline efficiency η_n was:

$$\eta_p = (H - \Delta h_p)\times 100\%/H \qquad (19)$$

Efficiency of pump device and pump station: Device efficiency of axial pump η_{sy} was the technical and economic index to reflect operation condition and decided by pump efficiency and pipeline efficiency together, that was:

$$\eta_{sy} = \eta\eta_p \qquad (20)$$

Many factors affect pump station efficiency, such as electric machine, the driving mode, pump, pipeline, inlet pool, outlet pool etc. So the axial pump station efficiency η could be expressed as follow:

$$\eta_{st} = \eta_g\eta_{tm}\eta\eta_P\eta_0 \qquad (21)$$

In the last written, η_g was the electric motor efficiency, η_{tm} was the driving efficiency and η_0 was the efficiency of inlet and outlet pool that the approximate number was 1.0 (Liu, 2001).

Head character expression: $H_T\infty$was the theoretical head of theoretical inviscid fluid gained under the condition of infinite number and thin blade. If the number of blade was finite and the theoretical head was H_T, the expression of $H_T\infty$ and H_T were:

$$\left.\begin{aligned}H_{T\infty} &= (u_2 v_{2u\infty} - u_1 v_{1u\infty})/g\\ H_T &= K\cdot H_{T\infty}\end{aligned}\right\} \qquad (22)$$

In the equation, μ_1 and μ_2 were the circumferential velocities at entrance and export of impeller, $v_{1\mu\infty}$ and $v_{2\mu\infty}$ were the components of absolute velocity on the circumferential velocity at entrance and export of impeller, K was the circulation coefficient of finite number blade pump and it could be calculated by the Stehekin equation. Therefore, the actual head of fluid in axial pump H was:

$$H = KH_T\infty\text{-}\Delta h_x\text{-}\Delta h_y\text{-}\Delta h_y \qquad (23)$$

The axial pump device head H_{sy} was the total head that the pipeline system conveying fluid requires, its number was equal to the sum of design net head and water piping system loss, that was:

$$H_{sy} = (Z_i\text{-}Z_0)+\Delta h_p \qquad (24)$$

In the last written, Z_i and Z_0 were the water level of inlet and outlet pool.

Power character expression: The shaft power of axial pump P should be the sum of effective power and various power loss in pump, that was:

$$P = P_e+\Delta P_m+\Delta P_v+\Delta P_h \qquad (25)$$

And the device power of axial pump P_{sy} should be the sum of shaft power and loss power in pipeline, that was:

$$P_{sy} = P+\rho g Q\Delta h_g \qquad (26)$$

PERFORMANCE PREDICTION AND EXPERIMENT

According to Eq. 1-26 formula, the mathematic model of axial pump and axial pump station could be established. Using Visual C++ software, the visual program of performance prediction could be developed. With inputting the basic parameters of axial pump or pump device, various function could be achieved, such as hydraulic loss calculation, performance prediction, drawing and revising curve and so on.

The Tianshan grade 1 pump station diverting water from the Yellow River built in 1972. 12 sets axial pump device were installed, the pump design head was 7.7 m and the design flow was 2.8 m^3 sec^{-1}. Accompanied by the operation, 0.7 billion stere water were raised and the local economy development was promoted greatly. But, due to the 30 years operation, a series of trouble of the pump station appeared, for example: Facilities aging, poor safety performance and low efficiency. To study the reasons and improve the operation conditions, site tests were carried out based on the site test procedures. One photograph of site test was as shown in Fig. 1. At the rated speed and different flow, the predicted data in contrast with actual measured data of pump head, shaft power and efficiency were as shown in Fig. 2(a-c), pump device's contrast were as shown in Fig. 3(a-c) and the essential performance curves of pump and pump device drew based on predicted data were as shown in Fig. 4a-b.

Fig. 1: Photograph of site test

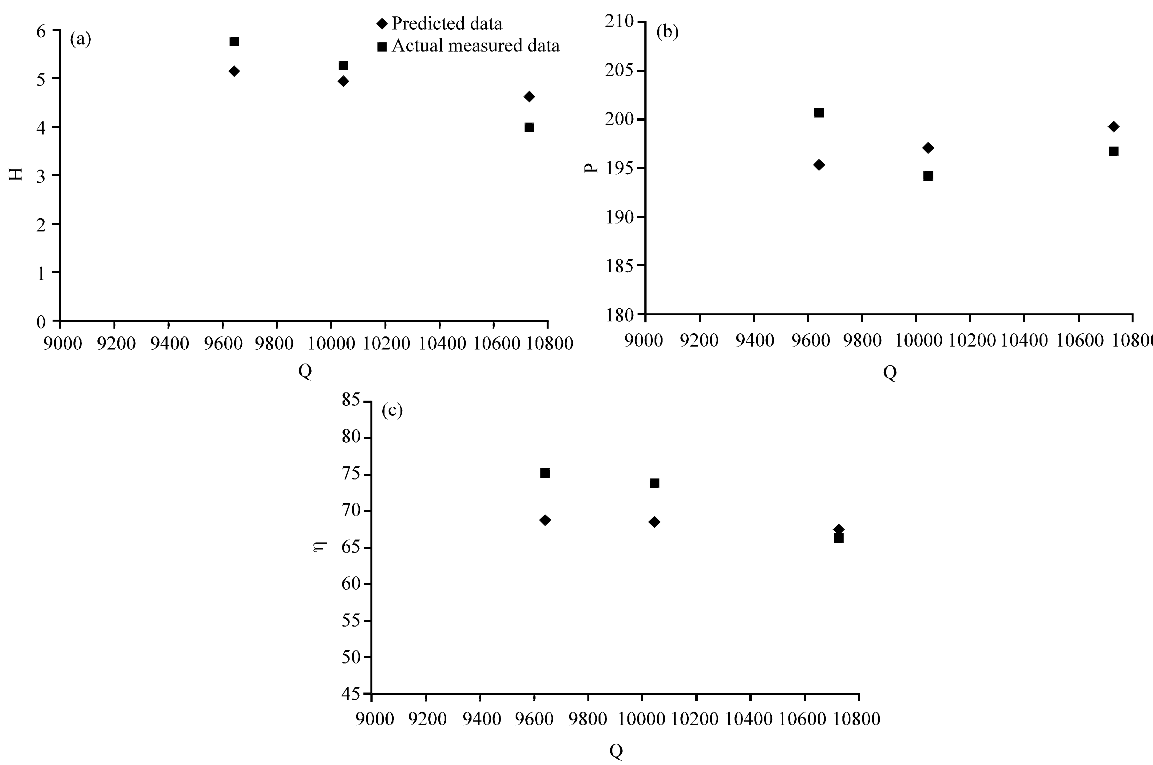

Fig. 2(a-c): Pump's performance contrast of predicted data and actual data (a) Head, (b) Shaft power and (c) Efficiency

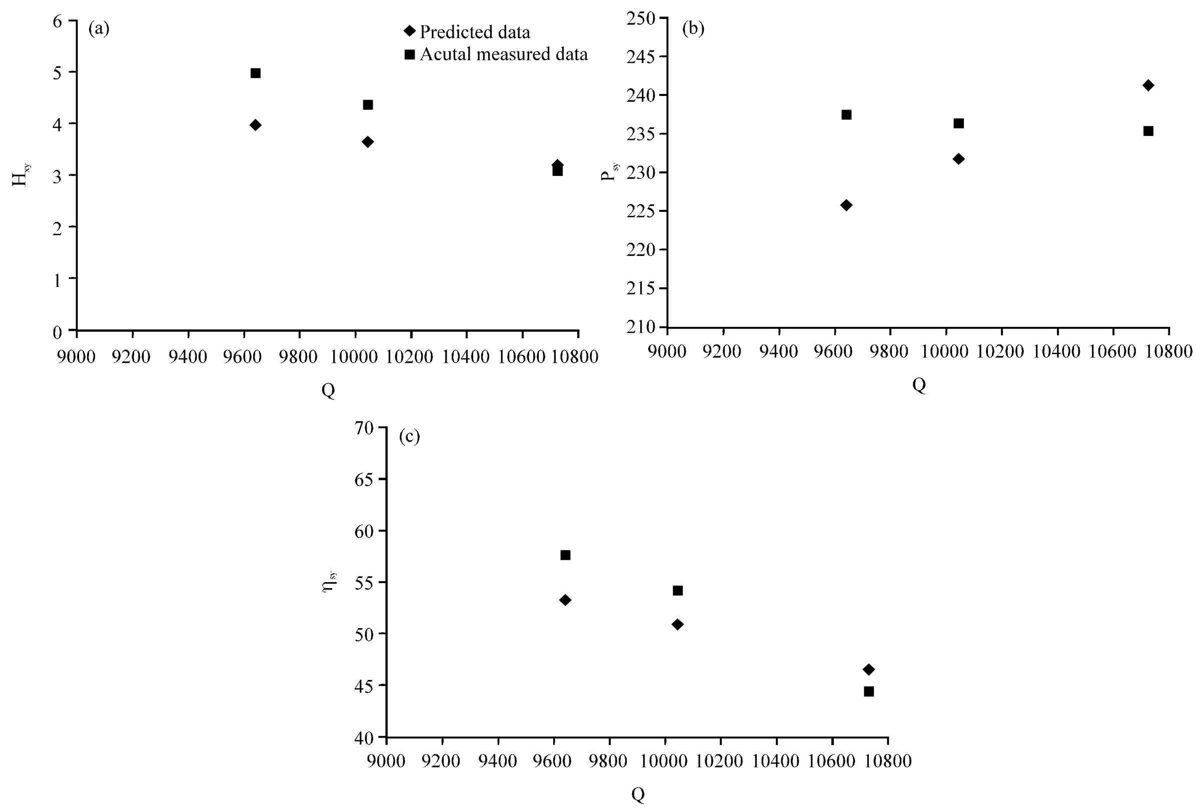

Fig. 3(a-c): Pump device performance contrast of predicted data and actual data (a) Head, (b) Power and (c) Efficiency

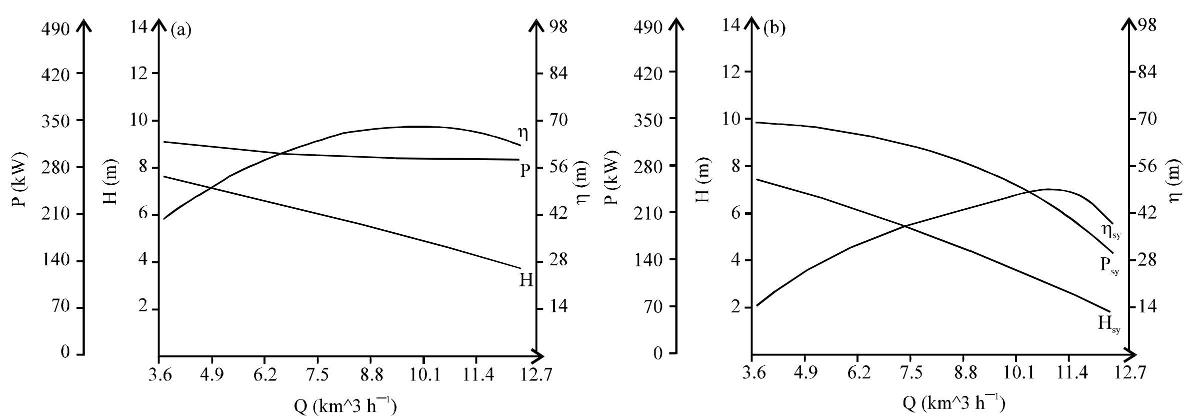

Fig. 4(a-b): Cruves draw by the program based on predicted data (a) Pump curves and (b) Pump device curves

CONCLUSIONS

Analyzing Fig. 2-4, it could be found: The difference of predicted data and actual measured data was small, especially at the design conditions. But the difference amplified when the flow deflected the design condition flow and the off design conditions, the greater the difference. The performance curves of pump and pump device drew by performance prediction program were reasonable and practicable after the contrast of actual measured data. In view of the error in site test and the increasing complexity of axial pump inner flow produced some adverse effects on the actual operation especially deflecting design condition, the predicted data was credible, the predicted model and application program was practical and the selection of various loss correction coefficient was reasonable. The study result can provide beneficial reference for design, technical reform and operation etc. It basically meets the needs of engineering and it has important reference value and practical significance.

Actually, the reform time of Tianshan pump station was shorten obviously. The efficiency was increased by 5% and the economic benefits were about 50 million yuan. So, it can be said that the aim of the research study was achieved.

Expectations: Based on the background of the technology renewal reform about TianShan grade 1 pump station, performance prediction using the hydraulic loss method for axial pump station device has a certain practicality but the difference between prediction data and actual measured data is larger as soon as deflecting design flow: The off design flow, the greater the difference. The main cause is the actual fluid flow in axial pump is very complex while deflecting design flow, so the actual loss is obvio usly larger than the prediction model loss based on design flow. Given all that, the following aspects of performance prediction study on axial pump and axial pump sta-tion need further development:

- Carry out more site tests, combine with the theoretical analysis to improve the practicability and accuracy of the loss model, consider adequately the internal loss reflection of axial pump in the prediction model as deflecting design flow and further improve hydraulic loss theory
- Combine with flow field calculation and analysis and build more precise mathematical relationships reflecting efficiently between the internal parameters and external characters
- Improve the universality of prediction software and develope higher practical integrated software for design and flow field analysis of axial pump

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