Using specific speed and standard basic parameters select single-stage and double-acting centrifugal pump

Xiaoming Zhu¹,a, Yonghai Yu¹,b,* and jingyuan Bai¹,c
¹College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, Jiangsu 210098, China
Email: axmzhu_hhu@163.com, b,yhyu@hhu.edu.cn, c,zhbjy@163.com

Abstract. Single-stage and double-acting centrifugal pumps are widely used in small and medium-sized irrigation pumping stations. It is difficult to assure data reliability and pump efficiency to select pump according to data sample from a specific pump manufacture chosen by the designer. A new method based on specific speed and basic parameters was studied in order to deduce the rotating speed and diameter of prototype pump’s impeller according to certain relative parameters of the model pump. At the same time, a special software for single-stage double-acting centrifugal pump selection was developed with Fortran and C# programming language. By typing in head and flow of certain pumping station engineering, proper rotating speed and diameter of prototype can be worked out. The method turns out to be reliable according to the verification based on the data of the Second Rate Pumping Station of certain pumping station.

1. Introduction
The single-stage and double-acting centrifugal pump has the advantages of high efficiency, large flow rate, compact structure and easy operation, compared with the single-stage and single-acting centrifugal pump, and it is widely used in small and medium-sized irrigation pumping stations.[1] The conventional selection method is to select several suitable pumps in the existing pump products according to the pump head and the pump station flow of the design conditions, and then the optimum scheme is obtained by comparison. This type of selection depends on the designer's choice of pump plant selection data, which has obvious limitations and is not conducive to the pre design of pump station before pump purchasing. With the development of computer technology, more and more scholars have devoted to the development of type selection software in the past 20 years. Most of their basic ideas are to establish a large database of pump products based on conventional selection methods, save manpower and make up for the limitation of selection results due to limited product materials [2-4]. In the development of large-scale axial pump selection software, Yonghai Yu and others [5-6] used the idea of conversion of the prototype model, so that the axial pump selection could not depend on product data.

In this paper, a new method of single-stage and double-acting centrifugal pump based on similarity theory is proposed. Collect product data of single-stage and double-acting centrifugal pumps produced by pump manufacturer[7], and establish a database of model pumps with specific rotation speeds of 60, 90, 130, 175, 190 and 280, which cover the scope of the centrifugal pump. Based on the similarity theory, define the flow coefficient CQ and pump head coefficient CH by the flow similarity law and the head of pump similarity law. From the performance parameters of the model pump and the flow rate and the head of pump coefficient, the related parameters of the prototype pump are deduced, and the software for the selection of single-stage and double-acting centrifugal pump based on the similar
theory is developed. The rationality and feasibility of the method are verified by the data of pump head and discharge of two stage pumping stations in an irrigation area.

2. Performance Curve of Centrifugal Pump Similar Parameters

2.1. Determination of Pump Head and Flow Coefficient

According to the similarity theory of vane pumps, the similarity rule of pump flow and head of pump is as follows. (Subscript M is the representation of model pump)

Flow similarity law equation:

\[
\frac{Q}{Q_M} = \left(\frac{D}{D_M}\right)^3 \left(\frac{n}{n_M}\right)
\]

Pump head similarity law equation:

\[
\frac{H}{H_M} = \left(\frac{D}{D_M}\right)^2 \left(\frac{n}{n_M}\right)^2
\]

In the program, \(D\) is the outlet diameter of pump impeller and unit is m, \(n\) is pump speed and unit is r/min, \(Q\) is pump flow and unit is m3/s, \(H\) is pump head and unit is m.

From the formula of flow similarity law:

\[
\frac{Q}{nD^3} = \frac{Q_M}{n_M D_M^3} = \text{constant}
\]

From the formula of pump head similarity law:

\[
\frac{H}{(nD)^2} = \frac{H_M}{(n_M D_M)^2} = \text{constant}
\]

In the program, the constant of the formula (3) determines the flow coefficient is \(C_Q = \frac{512Q}{nD^3}\), and the constant of the formula (4) determines the pump head coefficient is \(C_H = \frac{3600H}{(nD)^3}\).

2.2. Drawing of Performance Curve

The performance curve expressed by the flow and pump head coefficient is plotted according to the performance parameters and performance curves of the model pump. Because the pump manufacturer does not provide the actual mathematical expression of the performance curve, it is necessary to fit the performance curve of the model pump. At present, there are many researches on the fitting of pump performance curve. The function expression of fitting curve has power function form, exponential function form and polynomial form. Because of the high accuracy and wide application scope of polynomial fitting results, a set of \(n\) degree polynomials is used to represent the performance curve. The coefficients of polynomials can be determined by the least square method based on the measured data of the performance test or the known performance curves.

Generally speaking, the mathematical expression of the \(H\)-\(Q\) curve is expressed by a two degree polynomial, and the mathematical expression of the \(\eta\)-\(Q\) curve is expressed by a three degree polynomial, and its precision can be satisfactorily satisfied. Therefore, the \(CH\)-\(CQ\) curve is expressed by two degree polynomials, and the \(\eta\)-\(CQ\) curve is expressed by three degree polynomials. Taking S90 model pump as an example, the fitting curves of similar parameter performance curves are respectively: \(CH=-0.25CQ^2+0.14CQ+0.54\), and \(\eta=-26.34\times CQ^3-73.09CQ^2 +192.33CQ -10.42\). The similar parameter performance curve is shown in Figure 1.
3. **Methods and Steps of Selection**

A series of pumps that meet the "similar quasi number equal" condition have the same similar parameter performance curves, that is, the same set of similar parameter performance curves can represent a series of similar pump performance. Therefore, under the conditions of actual engineering head and flow rate, using the optimal efficiency point, to calculate the optimum speed and impeller diameter of the prototype pump according to the \( CH \sim CQ \) and \( \eta \sim CQ \) curves[9].

When the pump is selected, the pump head \( H \) and pump station flow \( QPS \) of the pump station are known. The methods and steps of selection based on the similarity theory are as follows.

I. The number of pump stations is \( I \), the single pump flow rate is \( Qi = QPS/i \). If we only know the design head of the pumping station, we need to estimate the head loss of the pipeline and get the pump head.

II. According to the curve \( \eta \sim CQ \) of each model pump, the flow coefficient \( CQ \) of the optimal efficiency point is obtained. Then obtain the head of pump coefficient \( CH \) from the \( CH \sim CQ \). The single pump flow \( Qi \) and the pump head \( H \) are substituted into formula (5) to calculate the each model pump’s speed which satisfy the flow and pump head of the highest efficiency.

\[
n = \frac{\sqrt[3]{512QiC_Q^2}}{\left(\frac{3600H}{C_H}\right)^3}
\]  

In the formula, \( H \) is the head of pump and unit is m, \( Qi \) is the flow of single pump and unit is m\(^3\)/s, \( CH \) is the coefficient of pump head when the efficiency of the model pump reaches the optimum point. \( CQ \) is the coefficient of pump flow when the efficiency of the model pump reaches the optimum point.

The small and medium irrigation pumping stations are usually equipped with asynchronous motors. Although the pump speed is calculated according to the formula (5), it is necessary to adjust the \( n \) value of the pump speed according to the speed value of the asynchronous motor. The synchronous speed of three-phase AC motor can be obtained by formula \( n = 6000/2p \), where \( 2p \) represents the number of magnetic poles of the motor. The number of motor magnetic poles of the single stage double suction centrifugal pump used in the medium and small irrigation pumping stations is basically within 10, and the synchronous speed of the motor is 3000 r/min, 1500 r/min, 1000 r/min, 750 r/min and 600 r/min. So the speed of asynchronous motor and pump has 2950r/min, 1450r/min, 970r/min, 730r/min and 585r/min.

In order to ensure that the prototype pump works in a highly efficient area, the regulation range of speed increase or deceleration is within 10% of the speed of prototype pump. This speed range adjusts the speed of different feasible schemes, and eliminates some unsuitable schemes.

III. According to formula (6) or formula (7), the impeller diameter \( D \) can be calculated.

\[
D = 8 \cdot \frac{3Qi}{nC_Q}
\]
\[ D = \frac{60}{n} \sqrt{\frac{H}{C_H}} \]  

(7)

In the formula, \( H \) is the head of pump and unit is m, \( Q_i \) is the flow of single pump and unit is m\(^3\)/s, \( C_H \) is the coefficient of pump head when the efficiency of the model pump reaches the optimum point. \( C_Q \) is the coefficient of pump flow when the efficiency of the model pump reaches the optimum point.

IV. The characteristic curve of the prototype pump is obtained by conversion of the comprehensive characteristics of the model pump according to the rotational speed of the prototype pump \( n \) and the calculated impeller diameter \( D \). The designer can analyze and compare the prototype pump performance curve under various selection schemes and select the most suitable solution.

4. Development of Selection Software

The development of selection software for single-stage and double-acting centrifugal pump using advanced programming language. Fortran language is used to write software curve fitting module, and C# language is used to design the interface of software, and the mixed programming of two languages is implemented by dynamic link library [10]. Because of the large number of transmission parameters, a simple method based on txt file transmission is used to realize data transfer between two languages. The advantages of Fortran in numerical calculation are fully played, and many characteristics of C# language are also used. The interface of selection of single-stage and double-acting centrifugal pump is shown in Figure 2.

![Interface of selection of single-stage and double-acting centrifugal pump](image)

Figure 2. Interface of selection of single-stage and double-acting centrifugal pump

At the time of selection, the user only needs to input the pump head, the pump station flow and the number of stations. The software will automatically calculate the single pump flow and select several alternative pump models from the hydraulic model database of the centrifugal pump. The corresponding rotational speed \( n \) and impeller diameter \( D \) of the prototype pump are calculated respectively, and the pump head and efficiency curves of the prototype pump are obtained according to the comprehensive characteristics of the pump section. The software provides a variety of methods for the conversion of the original model efficiency, including equal efficiency conversion, Ackeret formula conversion and IEC60193 formula conversion.

I. Equal efficiency conversion

In the conversion of hydraulic efficiency, the efficiency increment is negligible. There is a formula at the point of similar working condition.

\[ \eta_p = \eta_m \]  

(8)

In the formula, \( \eta_p \) and \( \eta_m \) is the hydraulic efficiency of the prototype pump and model pump, respectively.

II. Ackeret formula conversion

The formula assumes that half of the hydraulic loss of the model is eddy loss, and the other half is
friction loss.

\[
\frac{1-\eta_p}{1-\eta_m} = 0.5 + 0.5 \frac{Re_m}{Re_p} \tag{9}
\]

In the formula, \( \eta_p \) and \( \eta_m \) is the hydraulic efficiency of the prototype pump and model pump, respectively. \( Re_p \) and \( Re_m \) is the Reynolds number of the prototype pump and model pump, respectively.

III. IEC60193 formula conversion

The difference of hydraulic efficiency between the prototype pump and the model pump represents the difference of efficiency. The hydraulic efficiency of the prototype pump is the sum of the difference between the hydraulic efficiency and hydraulic efficiency of the model pump.

\[
\eta_{hp} = \eta_{hm} + \Delta \eta_h \tag{10}
\]

\[
\Delta \eta_h = (1 - \eta_{hm, opt}) \left( \frac{Re_{uref}/Re_{um}}{Re_{uref}/Re_{um,opt}} \right)^{0.16} \left( \frac{Re_{uref}/Re_{um}}{Re_{uref}/Re_{um,opt}} \right)^{2/3} \tag{11}
\]

In the formula, \( \eta_p \) and \( \eta_m \) is the hydraulic efficiency of the prototype pump and model pump, respectively. \( \eta_{hm, opt} \) is the efficiency of the optimal operating point of the model pump. \( \Delta \eta_h \) is the difference of the hydraulic efficiency between the prototype pump and the model pump. \( Re_{uref} \) is the maximum Reynolds number of pump in the calculation of blade outer line speed, and the number of \( Re_{uref} \) is \( 7 \times 10^6 \). \( Re_p \) and \( Re_m \) is the Reynolds number of the prototype pump and model pump, respectively. \( Re_{um, opt} \) is the Reynolds number of the optimal operating point of a model pump.

5. Example Selection

Taking the two stage pumping station in a certain irrigation area as an example (referred to “Second Rate Pumping Station” as follow). The Second Rate Pumping Station use eight double-stage and double-acting centrifugal pumps and ten single-stage and double-acting centrifugal pumps to supply water to two main trunk channels. The net head of Second Rate Pumping Station is 29.83m. The head of Second Rate Pumping Station is 32.83m when water head loss of pipeline takes into account. The design flow of each single-stage and double-acting centrifugal pump is 1.5m³/s.

Input the pump head and the single pump flow in the software, and get two selection schemes. The flow coefficient of optimum point of efficiency \( C_Q \), and corresponding pump head coefficient \( C_H \), and the speed of pump, and the impeller diameter are shown in Table 1.

| S/N | Model type | \( C_Q \) | \( C_H \) | Calculation value of proto pump speed (r/min) | Setting value of proto pump speed (r/min) | Impeller diameter (m) |
|-----|------------|----------|----------|-----------------------------------------------|------------------------------------------|----------------------|
| 1   | S130       | 1.715    | 0.443    | 555                                           | 585                                      | 0.880                |
| 2   | S175       | 2.910    | 0.420    | 752                                           | 730                                      | 0.730                |

Check whether the flow meets the requirements under the condition that the pump head is determined. Under the corresponding flow to calculate pump efficiency according to Ackeret formula, and the calculation results of each scheme are shown in Table 2.

| S/N | Model type | Checking flow(m³/s) | Pump efficiency(%) |
|-----|------------|---------------------|--------------------|
| 1   | S130       | 1.33                | 83.18              |
| 2   | S175       | 1.64                | 88.37              |

As shown in Table 2, scheme 1 does not meet the flow requirements under the pump head.
Therefore, this scheme is excluded. The scheme 2 meets the flow requirements and the pump efficiency is higher.

After the above comparison, the model S175 is finally chosen. The speed of prototype pump is 730r/min, and impeller diameter is 0.730m.

According to the type and basic parameters of the single-stage and double-acting centrifugal pump, the type 800S-32 single-stage and double-acting centrifugal pump is selected as the prototype pump. The characteristic curve of the prototype pump calculated by the Ackeret formula is shown in Figure 3.

![Figure 3. Characteristic performance curve of prototype pump calculated on Ackeret formula](image)

6. Conclusion

The selection method of single-stage and double-acting centrifugal pump based on similarity theory can’t depend on pump product data for pump selection. This new type selection method is more reliable and convenient than conventional selection method. The selection software developed has high practical application value.

In this paper, six pumps with different specific speed were selected as model pumps in the range of specific speed of single-stage and double-acting centrifugal pump. Considering the impeller cutting condition, we can basically ensure that the most suitable scheme is obtained under the flow and pump head of all actual projects. The type selection software of this paper is open, and the user can add other hydraulic model of the single-stage and double-acting centrifugal pump according to the needs, perfect the model base and expand the coverage of the software.

According to the working parameters of the pumping station, the speed and diameter of the pump can be obtained according to the selection method proposed in this paper. The model of the prototype pump can be obtained in the comparison of type and basic parameter standard of single-stage and double-acting centrifugal pump, so that the pumps selected by the selection software are ready-made products.

Acknowledgement

The authors gratefully acknowledge the financial supported by the Fundamental Research Funds for the Central Universities under project number 2016B42214 and supported by 2018 Water conservancy science and technology project of Jiangsu Province.

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