QUADRATIC REGRESSION - BASED ORTHOGONAL DESIGN AND NUMERICAL SIMULATION OF A NEW-TYPE AGRICULTURAL WELL PUMP
/
一种新型农用井泵的二次回归正交设计与数值模拟

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Abstract: *Currently, the Greenhouse Effect has caused great influence on the development of industry and agriculture. Considering the research development request of new-type agricultural deep well pump, the test research was taken to increase the efficiency of well pump using hydraulic design of impeller, the modern numerical CFD technology and the orthogonal test method based on quadratic regression. The experiment was carried out with two geometric factors including outlet angle and outlet width. Then ten impellers were designed as per the orthogonal testing schemes based on quadratic regression. The full flow field of the two-stage agricultural well pump including impellers and guide vanes under the design condition was simulated by CFD, finally obtaining the rated efficiency of each scheme. The influence mechanism of outlet angle and outlet width on efficiency was investigated through the orthogonal testing method. According to the calculation results, constrained quadratic regression equation of the efficiency was put forward. The result showed that it would be instructive to increase the hydraulic efficiency of the new-type deep well centrifugal pump for agriculture engineering by using the impeller maximum - diameter approach.*

Keywords: *Agricultural well pump; Hydraulic design; Quadratic regression; Orthogonal experiment; CFD*

摘要：*目前，温室效应已经对工业、农业造成了很深的影响。鉴于新型井泵的研究发展需要，通过运用现代数值CFD技术和二次回归正交试验方法及叶轮水力设计来增加新型农用井泵的效率。试验选取叶轮出口安放角和出口宽度两个几何因素，按二次回归正交试验方案，设计了10副叶轮。通过计算流体动力学技术对包含叶轮、导叶在内的两级新型农用井泵的全流场进行了设计工况下的三维流场数值模拟，得到了10组设计方案额定点的效率值。通过二次回归正交试验法研究了叶轮出口安放角、出口宽度对效率的影响规律，根据计算结果对新型农用井泵效率提出了二次回归约束方程。结果表明，采用叶轮极大直径设计法对提高新型深井离心泵的水力效率具有一定的参考价值。*

关键词：*农用井泵；水力设计；二次回归；正交试验；计算流体动力学*

INTRODUCTION

Due to the strict working conditions, the diameter of the submersible pump for agricultural well is limited by the well diameter when it works in the motor-pumped well, and the single-stage head of the pump can't be efficiently increased due to the limited space using the traditional design methods, especially regarding the performance of centrifugal pump[6]. Therefore, the maximum diameter design method of impeller was proposed for the first time [4, 8], this method was successfully applied to the 100SJ8 centrifugal pump for deep well. The theoretical analysis, numerical simulation as well as the experimental investigation showed that the single-stage head of the centrifugal pump for deep well had been improved dramatically and the efficiency was also higher than before. This method is highly superior to the traditional design method in the hydraulic design of the agricultural well pump.

According to the requirements of orthogonal test based on quadratic regression, 10 impellers of the 150QJ20 new-type agricultural well submersible pump were optimized using the maximum diameter method. After conducting two-stage full flow field CFD simulation using 10 groups of impeller with twisted return guide vane of the new-type agricultural deep well pump, and comparing the test results with the simulation results, the influence of two main geometric parameters including outlet width and outlet angle on the efficiency of the pump was found. The efficiency constrained quadratic regression equation of this type well pump was also obtained [9].

引言

泵一般在机井内工作，因外径受井径的限制，运用传统的设计方法，单级扬程不能有效的提高[6]。文献[4,8]第一次提出了一种深井离心泵叶轮极大直径设计法。采用叶轮极大直径设计法，对某典型的 100QJ8 型深井离心泵进行水力设计，数值模拟和试验研究结果表明，该设计方法对提高深井离心泵单级扬程取得了明显的效果，同时其效率较原有设计又不降低。这种方法相比较传统设计方法尤其适用于农用井泵。

文中采用叶轮极大直径设计法，对某典型的 150QJ20 型农用井泵进行水力设计，并进行二次回归正交试验，设计出 10 副叶轮。通过 CFD 对 10 组叶轮配合扭曲反导叶的方案分别对两级全流场进行数值模拟，分析模拟结果，以研究叶轮的两个主要几何参数即出口宽度、出口安放角对深井离心泵效率的影响规律，从而得到该类型农用井泵效率的回归约束方程 [9]。

MATERIALS AND METHODS

Hydraulic Design

Q_d - Flow rate (m^3/s);

H - Head (m);

n - Rotation speed (r/min) ;

Q - Flow (m^3/s);

n_s - Specific speed= $\frac{3.65n\sqrt{Q}}{H^{3/4}} = \frac{3.65.r/\min\sqrt{m^3/s}}{m^{3/4}}$.

P_i - Total pressure at inlet (Pa);

P_0 - Total pressure at outlet (Pa)

M - Moment of force ($N \cdot m$);

η - Efficiency (%);

β_2 - Vane outlet angle (°);

b_2 - Outlet width(mm);

x_j - Natural variables(Dimensionless);

z_j - Canonical variable (Dimensionless);

r - Asterisks arm (Dimensionless);

m – Factor.

材料与方法

水力设计

Q_d – 额定流量（m^3/s）；

n – 转速（r/min）；

Q – 流量（m^3/s）；

n_s – 比转速= $\frac{3.65n\sqrt{Q}}{H^{3/4}} = \frac{3.65.r/\min\sqrt{m^3/s}}{m^{3/4}}$；

P_i – 进口总压（Pa）；

P_0 – 出口总压（Pa）；

M – 力矩（$N \cdot m$）；

η – 效率（%）；

β_2 – 出口安放角（°）；

b_2 – 出口宽度（mm）；

x_j – 自然变量（Dimensionless）；

z_j – 规范变量（Dimensionless）；

r – 星号臂长度（Dimensionless）；

m – 因素数.

H – 扬程（m）；

The design parameters

The basic design parameters of the 150QJ20 agricultural well submersible pump is that, Q_d=20 m^3/h, single-stage head H=11m, speed n=2850r/min, n_s=128. 10 impellers were optimized according to orthogonal experiment.

设计参数

150QJ20 型深井离心泵的基本设计参数为额定流量 20 m^3/h，单级扬程 11 m，转速 2850 r/min。经计算，比转速 n_s=128，10 组叶轮通过正交试验要求来设计。

The maximum diameter design method of impeller

According to the relevant national standard, the allowable outer diameter and inner diameter of the 150QJ-type agricultural well pump are 143mm and 121mm respectively. Supposing the diameter of the impeller front shroud to be 119mm, the impeller diameter could achieve maximum, which was shown in Fig.1. Once the diameter of impeller's front cover was determined, then other parameters of the impeller can be determined. Seeing Tab.1 for the specific information, other parameters of this design could be found in [5].

(1) The diameter of the shaft and wheel hub

Matching power with *P*=11kW, minimum shaft diameter was calculated using the following formula:

极大扬程设计法

依据国家相关标准，150QJ 型农用井泵的外径及内径要求分别为 143mm 和 121mm。叶轮的前盖板设计为 119mm，叶轮的直径达到最大，如图 1 所示。一旦叶轮的前盖板尺寸确定，叶轮的其他尺寸也就确定了。表格 1 中表示了各个设计参数值 [5]。

（1）确定轴径和轮毂直径

配套功率 $P=11$kW 计算，最小轴径为：

$$d_{\min} = \sqrt[3]{\frac{M_n}{0.2[\tau]}} = 16 \text{ mm} \tag{1}$$

Φ16mm stainless steel shaft was selected, the wheel hub diameter was selected as follow:

$D_h = 22$ mm

(2) Impeller inlet diameter

$D_{j,k} = 3.75$

选用Φ16mm 的不锈钢轴，则轮毂直径 Dh=22mm

（2）叶轮进口直径

$D_{j,k} = 3.75$

$$D_0 = 1000 \times k \times \sqrt[3]{\frac{Q}{3600 \times n}} = 46.84 \text{ mm} \tag{2}$$

$$D_j = \sqrt{D_0^{\ 2} + D_h^{\ 2}} = 47.82 \text{ mm} \tag{3}$$

$D_i = 48$ mm was determined

(3) Impeller outlet width

According to the structure and experience, take b_2=(9～13) mm.

(4) Vane outlet angle

According to the structure and engineering experience, take β_2=(10°～25°).

Blade number z, wrap angle and hydraulic fillet radius of front and back cover plate was selected based on experience and graphing.

取 $D_j = 48$ mm

（3）叶轮出口宽度

根据结构和经验，取 b_2=（9～13 ）mm

（4）叶轮出口安放角 β_2

根据经验初选，由基本方程和全扬程公式验算，取 β_2=（10°～25°）.

叶片数 Z、包角及盖板水力圆角半径根据经验及作图选择。

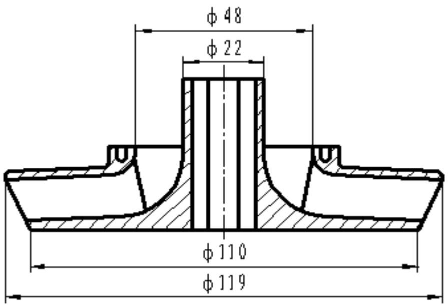

Fig. 1 - Cross-section of impeller

Table 1

Main structural parameters of the impeller

Structural parameters of impeller	Parameter selection
Blade number Z	6
Inlet vane angle β_1（°）	39
Wrap angle ϕ （°）	125
Impeller front covering plate D_{2max}（mm）	119
Impeller front covering plate D_{2min}（mm）	108
Impeller inlet diameter D_j（mm）	48
Wheel hub diameter d_h（mm）	22
Hydraulic fillet radius of front cover plate R_1（mm）	5
Hydraulic fillet radius of back cover plate R_2（mm）	18
Shaft diameter d（mm）	16

In order to reduce the production costs of the well pump, a new type of twisted return guide vane was selected to replace the common guide blades. Compared with the old space guide vane, the axial length of twisted return guide vane is shorter, and it is easier to be manufactured. The conventional return guide vane is pure cylindrical blades, its hydraulic loss is larger than common guide blades. The main innovations are as follows:

(1) The inlet of guide vane within φ100mm and φ121mm was twisted, its blades angle was selected basing on flow directions. This is the main differences between new twisted return guide vane and conventional return guide vane, which is also the main measure to reduce the hydraulic loss.

(2) The outlet diameter of the guide vane is φ48mm as shown in Fig.2.

(3) The middle part of guide vane's convex surface, which 2D cylindrical surface. The concave surface 3D surface and connected with vane inlet and outlet smoothly.

为降低深井离心泵的生产成本，设计了一种新型反导叶导流壳代替常用的空间导叶式导流壳。与传统的空间导叶的比较，它的轴向长度最短，且制造较容易。空间导叶容易其轴向长度的扭曲反导叶是短越来，而且很容易容易制作比旧的空间导叶。传统的反导叶是纯圆柱形叶片，其水力损失大于普通的导向叶片。主要创新点如下：

（1）导叶在 φ100mm 和 φ121mm 的入口处叶片是扭曲的，叶片的安放角根据流动方向选择。这是新的扭曲反导叶与常规反导叶之间的主要差异。也是减少水力损失的主要措施；

（2）导叶出口直径是 φ48mm 如图 2 所示；

（3）导叶的中间部分均为二维圆柱面。进口一段叶片是三维曲面。

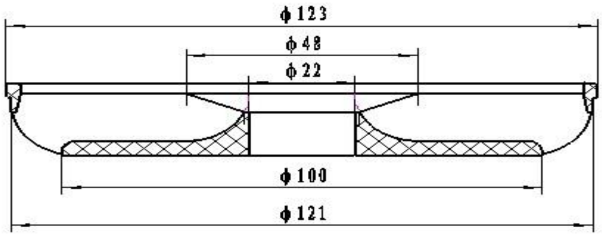

Fig. 2 - Cross-section of guide vane

Orthogonal testing method based on Quadratic regression

Using the point of mathematical statistics and principle of orthogonality, orthogonal testing method based on quadratic regression is a scientific method which is used to examine a number of factors simultaneously when these factors are under changing, For various factors in the changing circumstances; we use a normalized orthogonal table to arrange the test rationally. Orthogonal testing method based on quadratic regression uses combination design, which has the feature of less times of experiment, higher precision, simpler testing results treatment; meanwhile it could be optimized and analyzed [9].

The factors which affect the efficiency and head are Z, β_2, D_2, b_2, u_2 and so on. Based on professional knowledge and special design requirements of the new-type agricultural well, the following geometric parameters were taken into consideration: β_2 (vane outlet angle), b_2 (outlet width).

This study applied the orthogonal testing method based on quadratic regression to analyze the relationship among these factors such as β_2 (10°～25°), b_2 (9mm～13 mm) with the head and efficiency.

As the factor (m=2), if the frequency of zero level testing m_0=2, according to the formula of asterisk arm length r [3] (r =1.078).

According to the factor x_{1r}, for which the upper limit is 25°, the lower limit is 10 degrees, so the zero level (x_{10} =17.50), change interval (Δ_1 =6.96), upper level (x_{12} =24.46), lower level (x_{22} =10.54). The code of exit width b_2 (x_2) can be calculated similarly, shown in Table 2.

Considering the factor number ($m=2$), using orthogonal table L_4 (23) for transforming, two level test number ($m_c=2^2=4$), test scheme is shown in Tab.3. Other geometric factors were set according to the calculated values. 10 groups of hydraulic model were obtained.

二次回归正交试验

二次回归正交试验设计是一种处理多因素试验的科学方法，它采用数理统计学观点，应用正交性原理，对多个因素同时进行考查，在各个因素都处于变动的情况下，用一套规格化的正交表来合理地安排试验。二次回归正交试验采用组合设计，具有试验次数少，精确度高，试验结果处理简便，并可进行优化分析的特点 [9]。

影响效率与扬程的因素为 Z、β_2、D_2、b_2、u_2 等。在专业知识和设计的特殊需要的基础上，选取影响深井离心泵效率、扬程最重要的因素为叶轮出口安放角 β_2，出口宽度 b_2。

本研究应用二次回归正交试验分析这两个因素 β_2（10°～25°），b_2（9～13 mm）和效率、扬程之间的关系。

由于因素数 m =2，如果取零水平试验次数 m_0=2，根据星号臂长 r 的计算公式[3]，得到 r =1.078。

根据两个因素（ x_1 ）的上限 x_{1r} 为 25°，下限 x_{2r} 为 10°，所以零水平为 x_{10} =17.50，变化间距 Δ_1 =6.96，上水平 x_{12} =24.46，下水平 x_{22} =10.54。同理，可以计算出因素出口宽度 b_2（ x_2 ）的编码，见表 2。

由于因素数 $m=2$，选用正交表 L_4（23）进行变换，二水平试验次数 $m_c=2^2=4$，试验方案见表 3。其他几何因素按之前计算所得值设计，得到 10 组水力模型。

Table 2

Factors and levels

Canonical variable (z_j)	Natural variables (x_j)	
	x_1	x_2
Asterisks arm (r)	25.00	13.00
Upper level (1)	24.46	12.86
Zero level (1)	17.50	11.00
Lower level (-1)	10.54	9.15
Under asterisks arm (-r)	10.00	9.00
Changes in pitch (△$_j$)	6.96	1.86

Table 3

Experiment program

Test number	z_1	z_2	Vane outlet angle β_2 / (°)	Outlet width b_2 / mm
1	1	1	12.86	24.46
2	1	-1	12.86	10.54
3	-1	1	9.15	24.46
4	-1	-1	9.15	10.54
5	1.078	0	13.00	17.50
6	-1.078	0	9.00	17.50
7	0	1.078	11.00	25.00
8	0	-1.078	11.00	10.00
9	0	0	11.00	17.50
10	0	0	11.00	17.50

Numerical simulations

Governing equations

The over-current components of agricultural well pump consist of the inlet, several stages impeller and guide vane. The relative reference system fixed to the rotor with speed 2850r/min was adopted. The whole flow field was assumed to be 3-D incompressible steady viscous turbulent flow field. The calculation model was created based on the real machine; the whole flow domain of two stages consists of 5 components: inlet section, seal ring, impeller, guide vane, and outlet section, as shown in Fig.4. The outlet section extended to 2 times the impeller diameter length, so that the flow could be fully developed at the outlet. After modeled in Pro/E, the assembly model was imported to Gambit for further processing.

数值计算

控制方程组

深井离心泵的过流部件由进水节、 若干级叶轮和导叶体组成。采用固系于旋转叶轮上的相对参考系，转速为 2 850 r/min。设整个流道内部流场为三维不可压稳态粘性湍流场。整个计算模型建立在真实的流场中，整个流场如图 4，其包括 5 个部分：进口、密封环、叶轮、涡轮、出口，出口长度是进口长度的 2 倍以便于流体能够在出口处完全扩散。经过 Pro/E 建模后，整个模型导入 Gambit 中进行后续的运算。

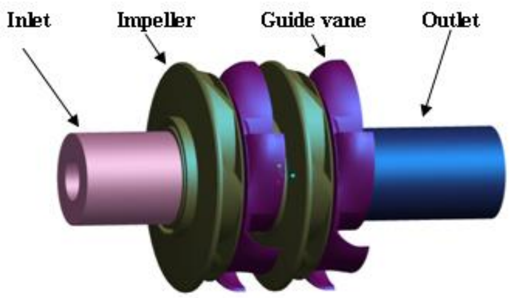

Fig.4 - Sketch of flow domain

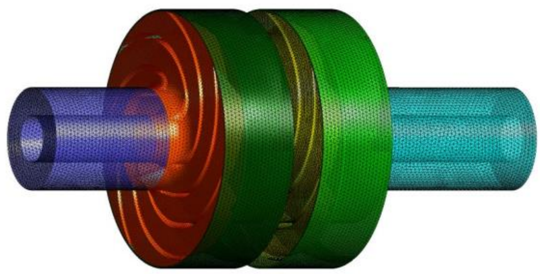

Fig.5 - Mesh mode

The properties of working media

The medium is water at room temperature and pressure with fixed density (ρ=998.2 kg/m^3) and dynamic viscosity (μ = 0.001003 kg / m·s).

Meshing of calculation region and the selection of calculation model

After modeled by Pro/E, the import section, impeller and guide vane were imported to the Gambit for further processing. The two stages full-flow field was meshed with structured and unstructured grids, shown in Fig.5. After comparing the five groups model grids between(1～2.5)million, the results showed that the efficiency fluctuates within 0.5% when the grid number surpass 1.75 million. Considering the performance of the computer, grid number of 1.75 million was selected.

The two stages flow channel of agricultural deep well

工作介质属性

在常温常压下介质为清水，密度为 998.2 kg/m3，动力粘度为 0.001 003 kg /m·s）。

计算区域网格划分及计算模型选取

在 Pro/E 中分别对进口段、叶轮、导叶筒体建模，导入 Gambit 中作进一步处理。完成两级全流场的计算区域构建后，进行网格划分，采用结构化网格和非结构化网格相结合的方法，如图 5 所示。比较 100 万到 250 万网格数之间的 5 组模型，发现在网格总量达到 175 万后，效率波动稳定在 0.5%以内，考虑计算机性能，选取 175 万网格数。

以深井离心泵的两级泵壳内流道为计算区域，采用全

pumps was taken as the computing area. At the same time, the whole calculation area was divided into two parts. The first is the import section of the pump and the rotating part of the impeller chamber. The second is the distorted-reversed guide vane static area. The connection surface between the two sub-regions is the interface. The coupling between the rotator and stator was simulated using Multiple Reference Frame (MRF).

Boundary condition

Supposing that the impeller inlet is irrotational flow [5], inlet surface center as the pressure reference point [1, 2, 3, 7, 10, 11], and the relative pressure is zero. The boundary condition of outlet is set to be outflow [4]. Solid-wall is supposed to be no slip. The turbulent flow of near-wall was handled by standard wall function [7].

Numerical algorithm and solution control parameters

The SIMPLEC algorithm and discrete difference equation of second-order upwind were applied. The factor coefficients of sub-relaxation for algebraic equations are as follows, pressure coefficient of Asian Relaxation is 0.3, momentum sub-relaxation factor 0.7, turbulent kinetic energy sub-relaxation factor 0.8, turbulent kinetic energy dissipation rate 0.8. The convergence precision is set to be 10^{-5}.

RESULTS ANALYSIS

Orthogonal combination design based on binary quadratic regression

Using numerical simulation of 10 sets of programs at rated conditions the efficiency value of deep well centrifugal pump, the table and results of orthogonal combination design based on dual quadratic regression were shown in Tab.4. According to the requirements of orthogonal combination design based on dual quadratic regression, centralization of the quadratic term of z_1^2, z_2^2, z_1', z_2' is shown in Tab .5.

流道方式，同时将整个计算区域分为泵的进口段与叶轮室的旋转部分和包括反导叶区的静止部分，两个子区域之间联接的平面作为分界面。对于旋转部分和静止部分之间的耦合，通过计算比较，采用多参考坐标系模型的定常计算结果进行泵的数值模拟。

边界条件

设叶轮进口为无旋流动[5]，进口面中心处为压力参考点 [1,2,3,7,10,11]，其相对压力为零；出口流动设为充分发展状态，即出流（outflow）形式[4]；固壁面无滑移，即壁面上各向速度均为零，对近壁面的湍流流动按标准壁面函数法处理[7]。

数值算法及求解控制参数

应用 SIMPLEC 算法，采用二阶迎风格式离散差分方程。代数方程迭代计算采取亚松弛，各项系数分别为压力亚松弛系数 0.3，动量亚松弛系数 0.7，湍动能亚松弛系数 0.8，湍动能耗散率 0.8 。设定收敛精度为 10^{-5}。

结果分析

二元二次回归正交组合设计

运用数值模拟得到 10 组方案在额定工况下深井离心泵的效率值，二元二次回归正交组合设计表及试验结果见表 4。根据二元二次回归正交组合设计的要求，将二次项 z_1^2 和 z_2^2 分别进行中心化，得到 z_1' 和 z_2'，二次项中心化结果见表 5。

Table 4

Design and test result of binary quadratic regression combination

Test number	Z_1	z_2	z_1z_2	z_1	z_2	z_1	z_2	y
1	1	1	1	1	1	0.368	0.368	64.46
2	1	-1	-1	1	1	0.368	0.368	66.74
3	-1	1	-1	1	1	0.368	0.368	66.54
4	-1	-1	1	1	1	0.368	0.368	67.44
5	1.078	0	0	1.162	0	0.530	-0.632	63.31
6	-1.078	0	0	1.162	0	0.530	-0.632	67.34
7	0	1.078	0	0	1.612	-0.632	0.531	65.29
8	0	-1.078	0	0	1.612	-0.632	0.531	67.25
9	0	0	0	0	0	-0.632	-0.632	66.46
10	0	0	0	0	0	-0.632	-0.632	66.46

Table 5

Binary quadratic regression combination design calculations (Part A)

i	z_1	z_2	z_1z_2	z_1'	z_2'	y	y^2	z_1y	z_2y
1	1	1	1	0.368	0.368	64.46	4 155.092	64.46	64.46
2	1	-1	-1	0.368	0.368	66.74	4 454.228	66.74	-66.74
3	-1	1	-1	0.368	0.368	66.54	4 427.572	-66.54	66.54
4	-1	-1	1	0.368	0.368	67.44	4 548.154	-67.44	-67.44
5	1.078	0	0	0.530	-0.63	63.31	4 008.156	68.25	0
6	-1.078	0	0	0.530	-0.632	67.34	4 534.676	-72.60	0
7	0	1.078	0	-0.632	0.530	65.29	4 262.784	0	70.38
8	0	-1.078	0	-0.632	0.530	67.25	4 522.563	0	-72.50
9	0	0	0	-0.632	-0.632	66.46	4 416.932	0	0
10	0	0	0	-0.632	-0.632	66.46	4 416.932	0	0
∑						661.29	43 747.09	-7.12	-5.29

Binary quadratic regression combination design calculations (Part B)

i	$(z_1z_2)y$	$z_1'y$	$z_2'y$	$(z_1z_2)^2$	$z_1'^2$	$z_2'^2$	z_1^2	z_2^2
1	64.46	23.721	23.721	1	0.135	0.135	1	1
2	-66.74	24.560	24.560	1	0.135	0.135	1	1
3	-66.54	24.486	24.486	1	0.135	0.135	1	1
4	67.44	24.817	24.817	1	0.135	0.135	1	1
5	0	33.554	-40.011	0	0.281	0.399	1.162	0
6	0	35.690	-42.558	0	0.281	0.399	1.162	0
7	0	-41.263	34.603	0	0.399	0.281	0	1.162
8	0	-42.502	35.642	0	0.399	0.281	0	1.162
9	0	-42.003	-42.002	0	0.399	0.399	0	0
10	0	-42.003	-42.002	0	0.399	0.399	0	0
∑	-1.38	-0.939	1.256	4	2.701	2.701	6.324	6.324

Notes: Owing to the limited space, Table 5 was divided into Part A and Part B.

According to Tab.4, each regression coefficient is listed below:

根据表 4 可知，各个回归系数分别为：

$$a = \frac{1}{n}\sum_{i=1}^{n} y_i = 66.129 \tag{4}$$

$$b_1 = \sum_{i=1}^{n} y_i z_{1i} \Big/ \sum_{i=1}^{n} z_{1i}^2 = -1.12653 \tag{5}$$

$$b_2 = \sum_{i=1}^{n} y_i z_{2i} \Big/ \sum_{i=1}^{n} z_{2i}^2 = -0.83693 \tag{6}$$

$$b_{12} = \sum_{i=1}^{n} y_i (z_1 z_2)_i \Big/ \sum_{i=1}^{n} (z_1 z_2)_i^2 = 0.345 \tag{7}$$

$$b_{22} = \sum_{i=1}^{n} y_i (z'_{2i})_i \Big/ \sum_{i=1}^{n} (z'_{2i})^2 = -0.465 \tag{8}$$

Therefore, the regression relationship (regression equation) between the standardized variables and test index is shown as follow:

因此，规范变量与试验指标 y 之间的回归关系式（回归方程）为：

$$y = 66.129 - 1.12653 z_1 - 0.83693 z_2 - 0.345 z_1 z_2 - 0.34799 z_1' + 0.46505395 z_2' \quad (9)$$

Variance analysis of orthogonal test based on quadratic regression

From Tab. 4, we know:

二次回归正交试验的方差分析

由表 4 可知：

$$\sum_{i=1}^{n} y_i^2 = 43747.09 \quad (10)$$

So the total variation can be expressed as:

所以有总变差为：

$$SS_T = \sum_{i=1}^{n} y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} y_i\right)^2 = 16.6395 \quad (11)$$

The variation of quadratic regression can be expressed respectively as follow:

二次型的回归变差分别为：

$$SS_1 = b_1^2 \sum_{i=1}^{n} z_{1i}^2 = 8.025755 \quad (12)$$

$$SS_2 = b_2^2 \sum_{i=1}^{n} z_{2i}^2 = 4.4297651 \quad (13)$$

$$SS_{12} = b_{12}^2 \sum_{i=1}^{n} (z_1 z_2)^2 = 0.4761 \quad (14)$$

$$SS_{11} = b_{11}^2 \sum_{i=1}^{n} z'_{1i}{}^2 = 0.327101 \quad (15)$$

$$SS_{22} = b_{22}^2 \sum_{i=1}^{n} z'_{2i}{}^2 = 0.584207 \quad (16)$$

Total regression variance could be expressed as follow:

总回归变差为：

$$SS_R = SS_1 + SS_2 + SS_{12} + SS_{11} + S_{22} = 13.84292 \quad (17)$$

Experimental error could be expressed as follow:

实验误差为：

$$SS_e = SS_T - SS_R = 16.63949 - 13.84292 = 2.796569 \quad (18)$$

Variance analysis is shown in Tab.6, the results show that, two partial regression coefficient reached significant level, in which

$F_{0.1}(1,4) = 4.54$

方差分析见表 6，结果表明，两个偏回归系数达到了显著水平，其中：

$F_{0.1}(1,4) = 4.54$。

Table 6

Variance analysis

Difference stems	Deviation quadratic sum (SS)	Free degree (d_f)	Estimate of variance (MS)	Statistical quantity F	Conspicuousness
z_1	8.025	1	8.026	11.479	**
z_2	4.429	1	4.429	6.336	**
z_1z_2	0.476	1	0.476	0.681	
z_1'	0.327	1	0.327	0.467	
z_2'	0.584	1	0.584	0.835	
Recurrence	13.842	5	2.768	3.959	
Residual	2.796	4	0.699		
Sum	16.639	9	1.848		

Quadratic regression equation of the efficiency

From the centralization formula of quadratic term, we know:

效率的二次回归约束方程

由二次项中心化公式，我们可得：

$$z_1' = z_1^2 - \frac{1}{n}\sum_{i=1}^{n} z_{1i}^2 = z_1^2 - 0.6324 \quad (19)$$

$$z_2' = z_2^2 - \frac{1}{n}\sum_{i=1}^{n} z_{2i}^2 = z_2^2 - 0.6324 \tag{20}$$

These formulas were substituted into the following equation, then we obtain:

代入回归方程，则有：

$$y = 66.129 - 1.12653z_1 - 0.83693z_2 - 0.345z_1z_2 - 0.34799(z_1^2 - 6.324/10) + 0.46505395(z_2 - 6.324/10) \tag{21}$$

According to the coding formula:

又根据编码公式：

$$z_1 = \frac{x_1 - 11}{3.71},\ z_2 = \frac{x_2 - 17.5}{13.91} \tag{22}$$

The quadratic regression-based constrained equation of the efficiency of the new-type deep well centrifugal pump for agricultural engineering could be expressed as follow:

代入上式，整理后可得新型深井离心泵效率的二次回归约束方程（回归公式）为：

$$y = 66.835 + 0.373x_1 - 0.0699x_2 - 0.0068x_1x_2 - 0.025x_1^2 + 0.0024x_2^2 \tag{23}$$

So η can also be expressed as follow:

故，η 也可表示为：

$$\eta = 66.835 + 0.373\beta_2 - 0.0699b_2 - 0.0068\beta_2 b_2 - 0.025\beta_2^2 + 0.0024b_2^2 \tag{24}$$

CONCLUSIONS

Based on the orthogonal testing method of quadratic regression and numerical calculation, the hydraulic model of the new-type deep well centrifugal pump was conducted using the numerical simulation of two-stage full flow field. The influence mechanism of impeller outlet angle, outlet width on the pump for agriculture was obtained, the conclusions are shown as follows:

(1) The single-stage head of the deep well centrifugal pump which was designed using the maximum-diameter method is improved greatly and the efficiency is also higher than before. And combining the numerical simulation and orthogonal test based on binary regression could optimize the design of the centrifugal pump while complying with the design requirements.

(2) Using the two levels of the whole flow field for numerical simulation on the multistage deep well centrifugal pump for agriculture could optimize the design more accurately.

(3) Through the 10 groups of design schemes obtained from orthogonal testing method based on quadratic regression, we find the influence mechanism of two main geometric parameters of impeller with outlet width and outlet angle on the efficiency of the pump, meanwhile the optimal regression equation of this type well pump was also obtained, which can provide references for the optimization target design of new-type deep well pump for agricultural engineering.

结论

在二次回归正交试验设计、数值计算的基础上，采用数值计算和样机试验验证相结合的方法，对新型深井离心泵的水力模型进行两级全流场数值模拟，得到叶轮出口安放角、出口宽度对深井离心泵性能的影响规律，结论如下：

（1）采用极大直径设计法设计的深井离心泵单级扬程高，效率也不降低，采用数值模拟与二次回归正交试验相结合，能够指导深井离心泵的设计，找到符合设计要求的优选方案；

（2）针对多级深井离心泵，采用两级全流场作数值模拟能够较为准确的指导设计；

（3）通过二次回归正交试验设计出10组设计方案，得出了叶轮两个主要设计参数出口安放角和出口宽度对深井离心泵效率的影响规律，并优选出回归方程，从而为实现对新型深井离心泵的优化设计目标提供了设计依据。

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