Structural Parameter's Optimization of LW-800 Type Drilling Fluid Centrifuge

Song Tao Jiu, Guo Jing Gui

School of Mechatronic Engineering, Southwest Petroleum University, Chengdu Sichuan 610500

Abstract: ***The study about a new LW-800 type drilling fluid centrifuge was carried out aimed at the small capacity can't meet the requirement of the solid controlling system to full displacement treatment. The optimization design model of multi-objective for the LW-800 type of drilling fluid centrifuge has been built up and optimization procedure has been designed according to the design requirements base on the basic theory of the decanter centrifuge. This drilling fluid centrifuge's main structure parameters also been optimized at the same time. This research may have practical significance in developing new product and improving the existing drilling fluid centrifuge's structure.***

Keywords: Drilling fluid; LW-800 type of centrifuge; Structural parameter; Mathematical model; Optimization design

1. Introduction

The centrifuge, as the last level solid controlling equipment of drilling fluid solid controlling system, is the main separation equipment to remove harmful solid phase and recycling the useful solid phase that in drilling fluid[1~4]. The LW-355 type of centrifuges 、LW-450 type of centrifuges and a few LW-600 type of centrifuges were general used in oil field. But from the site usage, the actual production capacity of these centrifuges were far less than the theoretical production capacity that provide by manufacturers. It will not be able to meet the production requirements of drilling fluid solid controlling system. For this problem, we carried on the preliminary design with optimization design method for a new LW-800 type drilling fluid centrifuge.

2. The design requirements of LW-800 type drilling fluid centrifuge

The requirements include the performance parameters of the suspension to be processed, the material parameters of drum and the basic requirement of the machine[5~10], etc.

2.1 The performance parameters of the suspension to be processed

This design is mainly used to deal with water-based compound drilling fluid, the liquid phase is water and the solid phase is mainly formation cuttings. the performance parameters of the suspension to be processed are as follows:

The density of liquid phase: $\gamma_1 = 1000\ \text{kg/m}^3$

The density of solid phase: $\gamma_2 = 2600\ \text{kg/m}^3$

The density of suspension: $\gamma_3 = 1200\ \text{kg/m}^3$

The density of wet-residue: $\gamma_4 = 2280\ \text{kg/m}^3$

The viscosity of suspension: $u = 0.0095\ \text{pa}\cdot\text{s}$

2.2 The material parameters of drum

We choose 2205 duplex stainless steel(00cr22ni5mo3n) as the material of the drum. The material parameters mainly contains the density of material, Poisson's ratio, elasticity modulus, ultimate strength and the yield limit of the material at design temperature.

The density of material: $\gamma_0 = 7.85\times10^3\ \text{kg/m}^3$

Poisson's ratio: $\varepsilon = 0.3$

elasticity modulus: $E = 2.1\times10^{11}\ \text{N/m}^2$

ultimate strength: $\sigma_b = 620\ \text{Mpa}$

yield limit: $\sigma_s = 450\ \text{Mpa}$

2.3 The basic requirements of the centrifuge

The design requirements contains processing capacity of suspension, screw transmission capacity, moisture content of sediment and the efficiency of screw transmission. Moisture content was ensured by the time that sediment stayed in the dehydration zone.

Processing capacity of suspension: $Q_s = 0.028\ \text{m}^3/\text{s}$

Screw transmission capacity: $\text{G}_s \geq 2.22\ \text{kg/s}$

Dehydration time of sediment: $T = 6\sim10\,\text{s}$

The efficiency of delivery sediment: $E_p \geq 90\%$

3. Optimization mathematics model of LW-800 type drilling fluid centrifuge

3.1Design variables

The mainly problem of this project is geometric structure parameters optimization. When the nominal diameter has been determined, the other main geometry parameters are as follows:

(1) The effective working length of drum L

(2) Radius of overflow mouth of drum R_1

(3) Radius of slag hole of drum R_3

(4) The half cone angle of drum α

(5) The rise angle of helical blade β

(6) The angle between the generating line of helical blade and the radial plane that perpendicular to the axis of drum θ

(7) The wall thickness of drum δ_1

Therefore, the design variables of the optimization design were as follows:

$$x=[L、R_1、R_3、\alpha、\beta、\theta、\delta_1]=[x_1、x_2、x_3、x_4、x_5、x_6、x_7]^T$$

3.2The objective function

The design indicators of optimization of structural parameters [11~15] for LW-800 type drilling fluid centrifuge contains the torque when spiral lose slag, axial forces, the weight of the centrifuge, the shaft power of centrifuge.

(1) The minimum torque of spiral lose slag $F_1(\overline{x})$

In the process of losing slag, there will be friction between sediment and drum, and between sediment and spiral. There will be a torque produced cause of the friction. The torque has a great influence to the strength of the auger conveyor and the discharge power of spiral. So it's very important to work out the torque. Formulas are as follows:

$$F_1(\overline{x})=\frac{G\,(\mathrm{ctg}\beta+\mathrm{ctg}\vartheta_1)\ (\omega-\dot{\varphi})^2\ (\Omega_2\cos\alpha+\Omega_1\sin\alpha\cos\beta)}{\Delta\omega\sin\alpha\qquad\qquad[\Omega_2-\Omega_1\ f_1\sin(\vartheta_1+\beta)]}\ f_1\cos\vartheta_1\ \frac{(R_1^{\ 2}-R_3^{\ 2})}{2}\qquad (\mathrm{N\cdot m})$$

$$(\Omega_1=\sin(\alpha-\theta)+f_2\sin\vartheta_2\cos(\alpha-\theta) \qquad (2)$$

$$\Omega_2=\cos(\alpha-\theta)-f_2\sin\vartheta_2\sin(\alpha-\theta)\cos\beta \qquad (3)$$

In the above formulas: ω —angular speed of drum, $\mathrm{rad/s}$;

$\dot{\varphi}$ —the relative angular speed between the sediment and the drum, take a positive when advance and negative when lag, $\mathrm{rad/s}$;

f_1—the coefficient of friction between sediment and the inner wall of the drum, $f_1=0.3$;

ϑ_1—the angle between the sliding direction of sediment along the drum wall and the radial plane that perpendicular to the axis of drum,°;

$\Delta\omega$—the difference of angular speed between drum and spiral $\mathrm{rad/s}$.

(2) The minimum axial force act on spiral $F_2(\overline{x})$

The axial force act on spiral is a important data that we need for bearing design. So it's very important to work out the axial force that act on spiral. Formulas are as follows:

$$F_2(\overline{x})=\frac{G(\omega-\dot{\varphi})^2\ (\mathrm{ctg}\beta+\mathrm{ctg}\vartheta_1)\,(R_1-R_3)\ [f_1\cos\alpha\sin(\vartheta_1+\beta)+\sin\alpha\cos\beta]}{\Delta\omega\sin\alpha\qquad\qquad[\Omega_2-\Omega_1\ f_1\sin(\vartheta_1+\beta)]}\cos\theta\cos\beta \qquad (\mathrm{N})$$

(4) (3) The lightest total weight of the machine $F_3(\overline{x})$

From the viewpoint of save material, the weight of the centrifuge machine is the lighter the better. When the weight of all the rotating parts have been determined, the total weight of the centrifuge was determined accordingly. So we need work out the total weight of the rotating parts. Formulas are as follows:

$$F_3(\overline{x})=W_g+W_l \quad (\mathrm{kg}) \quad (5)$$

In the above formula: W_g — the total weight of drum, kg;

W_l —the total weight of auger conveyor, kg

(4) The minimum power expend $F_4(\overline{x})$

From the viewpoint of energy saving, the power that expend by centrifuge is the less the better. We use double variable frequency motor and timing belt to drive in this centrifuge. When the shaft power of the machine have been determined, the power of the main motor was determined accordingly. We can work out the shaft power with formula as follows:

$$F_4(\overline{x}) = N_2 + 2N_3 + N_4 + N_5 \quad (\mathrm{KW}) \tag{6}$$

In the above formula: N_2 — the power required to make the material reach operating speed, KW;

N_3 —the power that expend by bearing friction, KW;

N_4 —the power expend by the friction between drum and the inner surface of material layer and air, KW;

N_5 —the power expend by sediment discharged, KW.

3.3 Constraint Condition

(1) The effective working length of drum L

The specific value of the effective working length of drum L and the nominal diameter of drum D, we call it draw ratio λ and $\lambda = L/D$. Consider the size of the centrifuge and the limit of the work-yard, the value range of draw ratio will be 1 to 2 is good.

$$g_1(\overline{x}) = 1 - x_1 / D < 0 \tag{7}$$

$$g_2(\overline{x}) = x_1 / D - 2 < 0 \tag{8}$$

(2) The radius of free liquid level R_1

The radius of free liquid level R_1 has a great influence of the depth of liquid pool h and decided the sedimentation area and the axial length of dehydration area. We often chose the radius of free liquid level of the centrifuge that used in industry R_1 / R_2 from 0.7 to 0.9.

$$g_3(\overline{x}) = 0.7 - x_2 / R_2 < 0 \tag{9}$$

$$g_4(\overline{x}) = x_2 / R_2 - 0.9 < 0 \tag{10}$$

(3) The radius of sediment outlet R_3

The value range of the radius of sediment outlet is $R_3 / R_2 = 0.6 \sim 0.7$. It was influenced by the time that sediment stayed in drum and the moisture content of sediment.

$$g_5(\overline{x}) = 0.6 - x_3 / R_2 < 0 \tag{11}$$

$$g_6(\overline{x}) = x_3 / R_2 - 0.7 < 0 \tag{12}$$

(4) The half cone angle of drum α

The half cone angle of drum is a sensitive parameter. It's has a great influence of the structure and performance of the centrifuge. The optimal range of the half cone angle of drum: $5^\circ < \alpha < 18^\circ$

$$g_7(\overline{x}) = 5^\circ - x_4 < 0 \tag{13}$$

$$g_8(\overline{x}) = x_4 - 18^\circ < 0 \tag{14}$$

(5) The rise angle of helical blade β

For some material that difficult to separate, it's difficult to lose slag. The value range of rise angle of helical blade will be $2^\circ \sim 4^\circ$. For some normal material, the value range of rise angle of helical blade will be $4^\circ \sim 6^\circ$. In this article, we chose The rise angle of helical blade from 2° to 6°.

$$g_9(\overline{x}) = 2^\circ - x_5 < 0 \tag{15}$$

$$g_{10}(\overline{x}) = x_5 - 6^\circ < 0 \tag{16}$$

(6) The angle between the generating line of helical blade and the radial plane that perpendicular to the axis of drum θ

We often define θ as $\theta = 0^\circ$ or $\theta = \alpha$. But form some data, these values were not the best angle. In this article, we define the values of θ as $0^\circ < \theta < 45^\circ$.

$$g_{11}(\overline{x}) = -x_6 < 0 \quad (17)$$

$$g_{12}(\overline{x}) = x_6 - 45^{\circ} < 0 \quad (18)$$

(7) Strength constraint

The wall thickness of drum δ_1 was decided by wall stress of drum σ and edge stress σ_M. The wall stress of drum σ and edge stress σ_M should be less than the material's allowable stress to meet the strength requirement.

$$g_{13}(\overline{x}) = \sigma - [\sigma] < 0 \quad (19)$$

$$g_{14}(\overline{x}) = \sigma_M - [\sigma]_M < 0 \quad (20)$$

In the above formulas: $[\sigma]$—the allowable stress of drum shell, Mpa;

$[\sigma]_M$—the allowable stress of drum edge, Mpa.

(8) Stiffness constraints

The biggest angle of shaft end should less than the maximum allowable of shaft angle.

$$g_{15}(\overline{x}) = (\theta_A、\theta_B)_{max} - [\theta] < 0 \quad (21)$$

The centrifuge system should meet the maximum allowable deflection limits.

$$g_{16}(\overline{x}) = w_{max} - [w] < 0 \quad (22)$$

In the above formula: θ_A、θ_B—the angles around the shaft at both ends, chose the bigger one, rad/s;

w_{max}—the maximum deflection of shaft, m;

$[\theta]$—the maximum allowable shaft angle, rad/s;

$[\theta] = 0.05$ rad

$[w]$—the maximum allowable deflection of shaft, m. $[w] = (0.000\ 3 \sim 0.000\ 5) \cdot l$, l is support span.

(9) The constraint of critical speed

The working speed of centrifuge n should avoid the critical speed n_l, in order to avoid resonance occur. Horizontal screw centrifuge is rigid shaft support, so $n < 0.75\, n_l$

$$g_{17}(\overline{x}) = n - 0.75\, n_l < 0 \quad (23)$$

(10) The time for sediment to stay in dehydration

The moisture content of sediment was influenced by the time for the sediment to dehydrate. If the time is less than 10 seconds, it has a big influence to the moisture content, and the moisture content of sediment become stable when the time is more than 10 seconds, a longer time won't have a big influence to moisture content. For a better dehydrate result, the time we chosen for dehydrate was 6 to 10 seconds.

$$g_{18}(\overline{x}) = 6 - T < 0 \quad (24)$$

$$g_{19}(\overline{x}) = T - 10 < 0 \quad (25)$$

(11) The efficiency of delivery sediment E_p

The E_p should greater than 85%, the angle of the sliding direction of sediment ϑ_1 should greater than 45°. It's better if the E_p is greater than 90% and ϑ_1 is greater than 55°.

$$g_{20}(\overline{x}) = 0.90 - E_p < 0 \quad (26)$$

$$g_{21}(\overline{x}) = 55^{\circ} - \vartheta_1 < 0 \quad (27)$$

(12) The production capacity according to suspension Q_h

The throughput of the centrifuge Q_h should to meet the design value $[Q_h]$, and $[Q_h] = 0.028\ m^3/s$.

$$g_{22}(\overline{x}) = [Q_h] - Q_h < 0 \quad (28)$$

(13)The maximum screw transmission capacity G_s

According to the design requirement, the throughput of LW-800 type centrifuge according to sediment G_s should to meet the design value $[G_s]$ and $[G_s] \geq 2.22$ kg/s

$$g_{23}(\overline{x}) = [G_s] - G_s < 0 \quad (29)$$

In the above formulas: G_s —the maximum screw transmission capacity, kg/s;

$[G_s]$ —the maximum screw transmission capacity according to design, kg/s.

3.4Optimization mathematical model of multi-objective

Consider screw torque, the axial force act on spiral in the process of transit, the total weight of centrifuge and shaft power at the same time, make multi-objective optimization on geometric structure parameters of LW-800 type drilling fluid centrifuge. The mathematical model of optimization is as follows:

$$\min F(\overline{x}) = \min [F_1(\overline{x}) \;\; F_2(\overline{x}) \;\; F(\overline{x}) \;\; F_4(\overline{x})]^T$$

$$
\begin{aligned}
s.t. \quad & g_1(\overline{x}) = 1 - x_1 / D < 0 \\
& g_2(\overline{x}) = x_1 / D - 2 < 0 \\
& g_3(\overline{x}) = 0.7 - x_2 / R_2 < 0 \\
& g_4(\overline{x}) = x_2 / R_2 - 0.9 < 0 \\
& g_5(\overline{x}) = 0.6 - x_3 / R_2 < 0 \\
& g_6(\overline{x}) = x_3 / R_2 - 0.7 < 0 \\
& g_7(\overline{x}) = 5^\circ - x_4 < 0 \\
& g_8(\overline{x}) = x_4 - 18^\circ < 0 \\
& g_9(\overline{x}) = 2^\circ - x_5 < 0 \\
& g_{10}(\overline{x}) = x_5 - 6^\circ < 0 \\
& g_{11}(\overline{x}) = -x_6 < 0 \\
& g_{12}(\overline{x}) = x_6 - 45^\circ < 0 \\
& g_{13}(\overline{x}) = \sigma - [\sigma] < 0 \\
& g_{14}(\overline{x}) = \sigma_M - [\sigma]_M < 0 \\
& g_{15}(\overline{x}) = (\theta_A \cdot \theta_B)_{max} - [\theta] < 0 \\
& g_{16}(\overline{x}) = w_{max} - [w] < 0 \\
& g_{17}(\overline{x}) = n - 0.75\, n_l < 0 \\
& g_{18}(\overline{x}) = 6 - T < 0 \\
& g_{19}(\overline{x}) = T - 10 < 0 \\
& g_{20}(\overline{x}) = 0.90 - E_p < 0 \\
& g_{21}(\overline{x}) = 55^\circ - \vartheta_1 < 0 \\
& g_{22}(\overline{x}) = [Q_h] - Q_h < 0 \\
& g_{23}(\overline{x}) = [G_s] - G_s < 0
\end{aligned}
$$

4. The determination of optimum method

4.1 The theory of multi-objective optimization

Under the regulation of the constraint conditions, optimization design parameters and meet multiple design index at the same time and get the optimal solution finally, we call this method multi-objective optimization. Commonly used method contains the main goal method, unified objective method and delaminating sequence method, etc. To solve the mathematical model of optimization with main objective method and unified objective.

1) Main objective method

The main objective method is a method that chose a sub-goal from all the objectives and regard it as main goal, and the other goal as the constraint condition, the constraints limit the original sub-goal function value within a certain range and the result of sub-goal won't too bad.

(2) Unified objective method

The unified objective method is a method that turn the sub-goal functions to an evaluation function through a certain relationship, turn it into a single objective problem and solve it. Transform method of evaluation function are as follows: goal programming method, the legal battles method, the linear weighting method, square and weighting method, etc.

Establish evaluation function with linear weighting method:

$$\min F(\overline{x}) = W_1 F_1(\overline{x}) + W_2 F_2(\overline{x}) + W_3 F_4(\overline{x}) + W_4 F_4(\overline{x})$$

$$\text{s.t.} \quad g_1(\overline{x}) \sim g_{23}(\overline{x}) < 0$$

(30)

In the above formulas: W_i —weighting factors, $\sum_{i=1}^{l} W_i = 1$.

We divided W_i into two weighting factors:

$$W_i = W_{1i} \cdot W_{2i}$$

In the above formulas: W_{1i}—the weighting factor that reflect the relative importance of each design index.

W_{2i} —the weighting factor that adjust the objective function value's influence with different orders of magnitude.

4.2A composite algorithm for mixed discrete variable

The question about structure parameter optimization for LW-800 type drilling fluid centrifuge is a question about mixed discrete variable. The discrete variable optimization method is need to solve the optimization mathematical model. Commonly used method contains mixed integer optimization method, discrete variable combination optimization method, etc. In this article we use the discrete variable combination optimization method to solve the optimization mathematical model. The discrete variable combination algorithm [16,17] is a combination algorithm method that based on discrete complex method, and add some miscellaneous functions such as welt search, speed up, composite reconstruction, point check finally, etc. The functional block diagram just shown as Figure 4-1.

5. The Determination of Optimization Results

Compared the optimization results of main objective method and unified objective method, and we determined the structure parameters of LW-800 type drilling fluid centrifuge finally. The parameters form is as follows:

Table 1 structure parameter of LW-800 type centrifuge

<table>
<tr><td rowspan="3">Initial parameters</td><td colspan="2">Design variables</td><td>L</td><td>R_1</td><td>R_3</td><td>α</td><td>β</td><td>θ</td><td>δ_1</td></tr>
<tr><td colspan="2">Initial value of variables</td><td>1.600</td><td>0.320</td><td>0.260</td><td>10</td><td>5</td><td>10</td><td>18</td></tr>
<tr><td colspan="3">Initial value of objective function</td><td colspan="3">$F_1(x^{(0)})$=17407 N·m</td><td colspan="3">$F_2(x^{(0)})$=152799N</td></tr>
<tr><td rowspan="5">Optimization results</td><td colspan="9">Weighting coefficient：W_1=0.038 W_2=0.038 W_3=0.841 W_4=0.083
Evaluation function：$F(\bar{X})$=4880.7</td></tr>
<tr><td colspan="2">Design variables</td><td>L</td><td>R_1</td><td>R_3</td><td>α</td><td>β</td><td>θ</td><td>δ_1</td></tr>
<tr><td colspan="2">Optimization variables</td><td>1.520</td><td>0.315</td><td>0.265</td><td>11</td><td>3.4</td><td>15</td><td>15.5</td></tr>
<tr><td colspan="3" rowspan="2">Optimal solution of objective function</td><td colspan="3">$F_1(x^*)$=9800.104 N·m</td><td colspan="3">$F_2(x^*)$=90873.36 N</td></tr>
<tr><td colspan="3">$F_3(x^*)$=1238.857 Kg</td><td colspan="3">$F_4(x^*)$=159.0389 KW</td></tr>
</table>

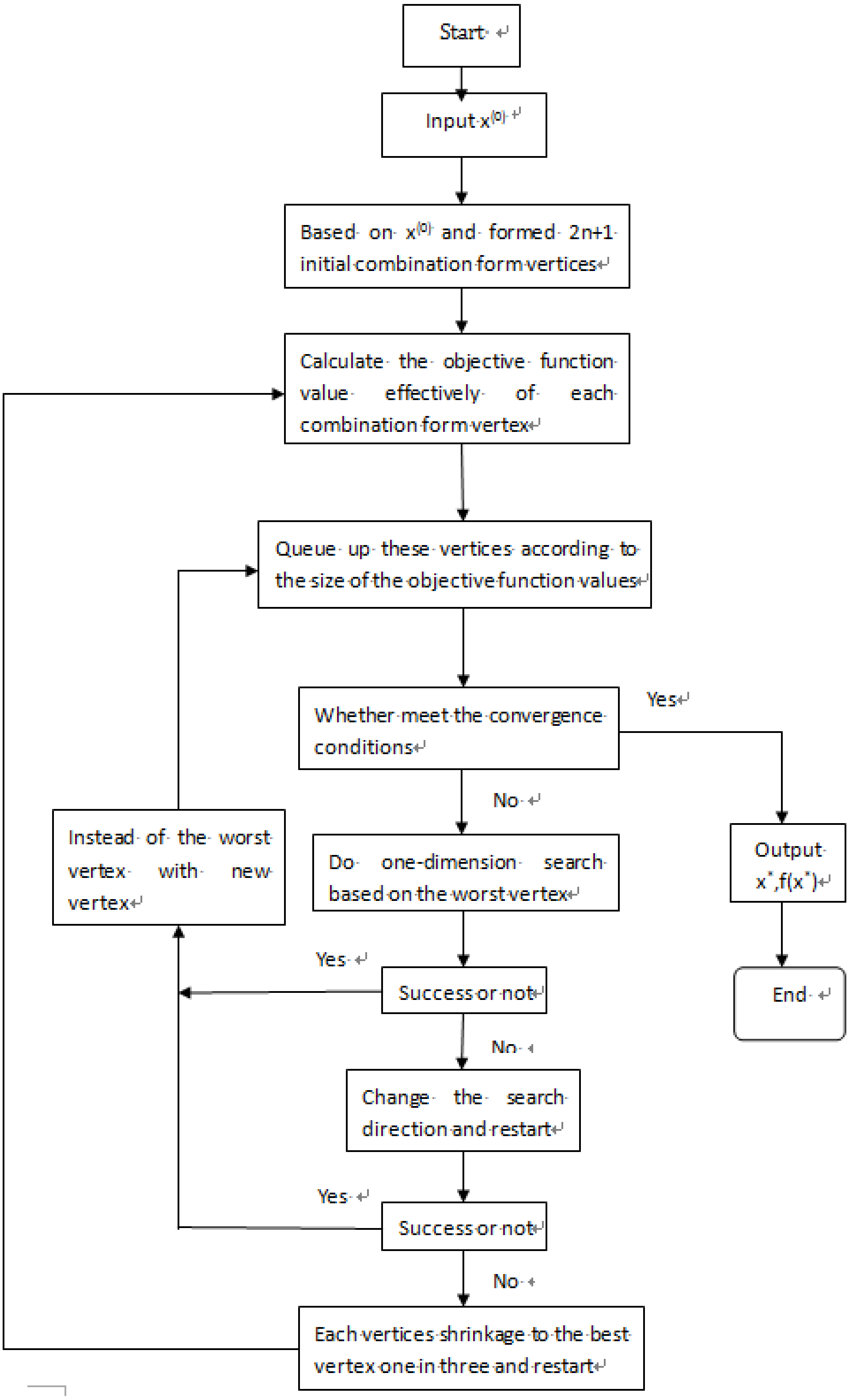

Figure 1: The functional block diagram of discrete variable combination algorithm

6. Conclusion

1) After optimization and compared to normal design, the torque decrease 43.7%, axial force decrease 40.5%, the total weight of axisymmetric body decrease 6.8%, power loss decrease 15.4%. The now design is more conserve fabric, energy saving, wear less and work longer.
2) The program modules that established in this article are based on mature basic theory of centrifuge. With these program modules, the cycle of design for centrifuge can be cut down a lot.
3) The solving program and mathematical model that established in this article for structure parameters optimization design of centrifuge have a great generality. It have some practical significance for the improvement of existing drilling fluid centrifuge and development new

type of centrifuge.

References

[1] Sun Q C, Jin D W. Principle Structure and Design Calculation of Centrifuge[M]. Beijing: China Machine Press,1987.3.
[2] Liu H B. Study on Performance Theory of Drilling Fluid Centrifuge[D]. Chengdu: Southwest Petroleum University,2006.
[3] Pan Y M, Li S T. Chemical Machine part ii(fourth edition)[M]. Beijing: Chemical Industry Press,1987.6
[4] Chen H S. Service Behaviour Research of Decanter Centrifuge[D]. Dongying: China University of Petroleum,2007.
[5] Zhang E, Mai M T M. Modern Design Theory and Method[M]. Beijing: Science Press,2007.
[6] Xu k. the design of the drilling fluid centrifuge[J] . China Petroleum Machinery,1990,18(5):14-20.
[7] Sun K D, etc. Development of LW1200 ×1980N Horizontal Scroll Decanter[J] . Fluid Machinery,2003.31(4):26-28.
[8] Dong H R, Wang T L, Etc. The development of model LW400 ×1200 of high-speed centrifuge with automatic frequency control system [J]. Oil Field Equipment,2006.31(1):32-36.
[9] Wang C H, Dong H R, Cheng X G, etc. The decision of structural parameters of sedimentation area and influencing factor analyses of the centrifuge[J]. Oil Field Equipment, 2006,35(5):27-30
[10] Shi J M, Zhu P, Zhang J H, etc. The CAD system of separation machinery (Ⅰ)-the optimization design of centrifuge's technology and operating parameters[J] . Chemical Engineering & Machnery,1995.22(6):328-332.
[11] Chen L Z. Mechanical Optimum Design Methods(second edition) [M]. Beijing: Metallurgical Industry Press,1995.
[12] Sun J M. Mechanical optimization design(third edition) [M]. Beijing: China Machine Press,2006
[13] Peng G L. program design with Fortran 95[M]. Beijing: China Electric Power Press,2002.9.
[14] Shi N X. discussion on power calculation and saving energy for centrifugal machine[J]. Petro-Chemical Equipment Technology,1995.16(1):36-39.
[15] Zhao H X. Li J S. Li X R, etc. A optimized formula of the thread pitch of the rotary screw conveyors[J] . Journal of Luoyang Technology College,1997.7(2):27-32.
[16] Chen L Z, Sun C X, Li X R. A composite algorithm and program-MDCP for mixed discrete variable[J]. Journal of Beijing Iron and Steel Institute,19879(4):73-80.
[17] Chen L Z. optimization design method of discrete variable in engineering-principle and application[M]. Beijing: China Machine Press,1989.