Characteristics improvement of labyrinth screw pump using design modification in screw

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Abstract. The labyrinth screw pumps are widespread in the chemical and oil industries. The scope of the possible use of the labyrinth-screw pumps working in aggressive mediums is much wider in comparison with the pumps with similar pressure and flow parameters. This is due to the type of operation and lack of the mechanical friction of the parts. Increasing the pump flow rate can be achieved by reducing hydraulic friction resistance or profiling the inlet and outlet of the fluid flow. The flow channel of the labyrinth screw pump has been improved and a new design of its movable operating elements has been developed based on the proposed concept of jet resistor diodes. The reduction of hydraulic resistance in the flow channel of the pump with the working fluid flow in the forward direction and increasing the resistance of the diode made it possible to obtain a more efficient design. The results of improvement are compared with experimental data. The simulation of the flow in the pump is performed by solving the RANS equations with the SST turbulence model. The flow predictions in the flow section are obtained. The flow rate characteristics of typical and developed pumps are calculated. The developed pump design allows for increasing its flow rate by almost 10%. At the same time as the flow rate of the pump increases its power output. The efficiency of the industry-developed labyrinth screw pump application is proven by comparing the flow rate characteristics of the pumps.

1. Introduction
The current level and further development of technology are inextricably linked with the intensification of the hydraulic systems and unit operation, improving their technical level and competitiveness. Labyrinth Screw Pumps (LSP) are widely used in the chemical industry and oil production at specific speed values \( \omega_p = 0.5...2 \). It is advisable to improve their performance, reliability, and energy conservation [1-3] on the basis of the theory of work process developed on the basis of a generalized physical model, design methodology, which is the basis for improving the technical level and improving the design [4]. Due to the peculiarities of the work process and the absence of mechanical friction of parts,
the scope of the possible use of LSP when working on the aggressive medium is much wider compared to pumps with similar specific speed [5-7].

2. Literature Review

The work process of the pump depends on the shape of the screw and the fixed sleeve. In papers [5, 8] the results of LSP studies with simplified screw configuration and the possibility of using more durable materials are presented. But it does not improve the performance, but only increases the resource life. In [1, 6, 9-11] the results of LSP investigations with triangular screw and sleeve shape are presented. LSP characteristics are shown, but they can be improved by increasing the flow diode. An option to improve LSP characteristics is to use different screw shapes from triangular to trapezoid, circle, or rectangle [3, 11-13]. The best flow channel was not achieved. The best tool for flow channel research is CFD modeling in the pump [1-3, 14-16]. This approach was implemented in [1, 13], but the characteristics were found without visualizing the flow. The flow visualization, presented in [2, 3, 9, 10], does not allow to determine the optimal shape of the screw and sleeve, because of the study of only one shape without comparison with others. All this suggests that it is advisable to study the perfect design and flow visualization in it.

The LSP given in [11, 17, 18] have cone-shaped bushings at the inlet and outlet of the pump, and the movable operating elements with cuts in the form of a circle, trapezoid, and triangle. Operating elements with triangular cuts should be used when we want to obtain the maximum pressure at the outlet of LSP. For smaller pressures, semicircular and trapezoidal cuts should be preferred. Their hydraulic performance is better and less dependent on the gap between the screw and the sleeve. The disadvantages of this pump are the high hydraulic resistance of the multistage screw grooves. This reduces the efficiency and pressure at the pump outlet, increases the cavitation likelihood due to the flow complexity in the screw grooves.

According to the generalized physical model of LSP, flow moves in two opposite directions: from the pump inlet to the outlet (direct flow) and from the pump outlet to its inlet (reverse). The direct flow is caused by the rotation of the screw. The reverse flows through the gap between the protrusion of the sleeve and the screw under the action of pressure drop between the outlet and the inlet of the pump or the action of the working fluid weight if the pump is not horizontal [12]. According to the refined physical model of LSP workflow, the average pump flow rate is determined by the formula [12]:

\[ q_{\text{avg}} = z \left[ q_1(n) - q_2(\Delta p_{out}) \right], \] (1)

where \( z \) is the number of screw twist; \( q_1(n) \) is the flow rate caused by the displacement of the working flow volume contained in the screw groove of the pump for one rotation of the screw; \( q_2(\Delta p_{out}) \) is the flow rate caused by flowing into the groove of the pump through the gap formed by the projection on the sleeve and the recesses of the screw, under the action of pressure drop at the inlet and outlet of the pump \( \Delta p_{out} = p_{out} - p_{in} \) and self-weight, in case of the non-horizontal arrangement of the pump.

An increase in LSP flow rate depends on an increase in the flow rate \( q_1(n) \) and a decrease in the flow rate \( q_2(\Delta p_{out}) \), ie, by profiling its flow channel [7, 12]. Increasing the flow rate \( q_1(n) \) can be achieved by reducing the hydraulic friction resistance and profiling the inlet and outlet of the flow [19].

3. Research Methodology

The study was carried out in three stages. First, the flow between the screw and the sleeve was investigated using the OpenFoam open-source CFD software. In the second stage, an improved design of LSP based on the increase in diode resistance is proposed. After that, the flow characteristics of a typical and developed pump were calculated. A comparison of experimental and calculated data are made.
4. Results

4.1 Concept of jet resistor diodes
To reduce the flow rate \( q_2 (\Delta P_{\text{out}}) \) it is proposed to use the design concept of jet resistor diodes. The reduction of the reverse flow is achieved by a significant deformation of the flow, which is accompanied by its separation from the walls, collision of the jets and other hydrodynamic phenomena [20, 21]. The diodes are rated by flow rate \( Q_D \) and resistance \( \zeta_D \):

\[
D_0 = \frac{Q_{\text{dir}}}{Q_{\text{rev}}}, \quad \zeta_D = \frac{\zeta_{\text{dir}}}{\zeta_{\text{rev}}}
\]

where \( Q_{\text{dir}} \), \( Q_{\text{rev}} \), \( \zeta_{\text{dir}} \), \( \zeta_{\text{rev}} \) are the flow rates and hydraulic resistance coefficients when the fluid flows through the diode in the direct and reverse directions, respectively.

In resistors, the diodicity by the flow rate associated with the diodicity by the resistance \( D_0 = \sqrt{\zeta_D} \). Using the concept of jet diodes will increase the flow rate and efficiency of LSP [22].

4.2 Design of LSP
The peculiarity of the improved design of LSP operating elements (Fig. 1) is that the inlet and outlet of the sleeve and screw in the screw grooves made of chamfers. The length of the chamfer is equal to the four hydraulic radii of the screw groove of the sleeve and screw. The chamfers at the inlet of the sleeve and screw are made in the form of a confuser, with a taper angle of 20°...60°. The chamfers on the side of the outlet chambers are made in the form of a diffuser with a taper angle of 8°...15°. The edges at the inlet and outlet of the screw grooves of the sleeve and screw are blunt. This implementation ensures minimal hydraulic losses in LSP during the direct flow and increases its energy efficiency.

Figure 1. Labyrinth screw pump: (a) design; (b) cross-section; (c) section along the axis of the screw:
1 – drive shaft; 2 – screw; 3, 8 – multi-way screw grooves of elongated shape; 4 – the body; 5, 6 – inlet and outlet chambers; 7 – fixed sleeve.

The inner surface of the sleeve and the outer surface of the screw are made of multi-directional elongated multistage elliptical grooves. The width of the multi-pass screw grooves at the intersection on the outer surface of the screw is equal to the width of the multi-pass screw grooves on the inner surface of the fixed sleeve and the four hydraulic radii \( R_\theta \).

4.3 Computational model
To substantiate the proposed concept of improving the flowing channel of LSP, the fluid pattern in the pump was calculated.

The mathematical model consists of the Reynolds-averaged Navier-Stokes equations [23, 24] and the SST turbulence model [25]. This model is validated for the calculation of flow in LSP [26, 27] and
allows obtaining sufficient precision the separation zones in the screw groove and to trace the vortex formation [28].

**Figure 2.** Velocity vectors in the section along the axis of the typical screw design with different screw positions relative to the fixed sleeve.

**Figure 3.** Velocity vectors in the section along the axis of the improved screw design with different screw positions relative to the fixed sleeve.

**Figure 4.** Velocity vectors in the section along the axis of the improved screw design with different screw positions relative to the improved fixed sleeve.

The mathematical model is solved in the OpenFoam software package distributed with a free license, which allows it to be used for commercial and scientific purposes [27].
A standard solver based on the volume control method with a pressure algorithm was used. The fluid was incompressible. The calculations were carried out until the flow rates stopped varying by iterations and the values of the residuals of all equations did not reach values $10^{-5}$.

Four grid partitions were used: 1, 4, 9 and 20 million elements. In studies of the effect of grid partitioning, it has been found that starting from a mesh of 9 million elements, the values of the integral parameters have ceased to change [25, 26].

During the operation of LSP, there is a constant displacement of the projections of the screw relative to the sleeve, which is reflected in the modeled flow (Fig. 2, 3 and 4). The analysis of the flow patterns, especially when the sleeve is displaced relative to the screw by 0.5 twists (lead of screw), indicates that the offered forms have a significant diodicity. Improved flow part of LSP has a higher diodicity, i.e. better output characteristics. This confirms the proposed concept to improve the flow channel of the LSP working bodies.

4.4 Pump performance

To obtain a universal relationship between the average outlet flow rate of the pump and the dimensions of different working body shapes, their dimensions were determined through the hydraulic radius $R_h$. The flow rate caused by the displacement of the working fluid volume contained in the screw groove of the pump was determined by one screw rotation depending on

$$q_i(n) = k_{wv}A_kL_k\frac{n}{60}.$$  

where $n$ is the speed of the screw, rev/min; $A_k$ is the intersection area of the screw channel; $L_k$ is the length of the screw line; $k_{wv}$ is the coefficient that takes into account the real volume of the helical channel:

$$k_{wv} = \frac{A_kL_k - A_k(4R_k + b) + \frac{4}{3}\pi(2R_k)^3}{A_kL_k};$$  

(4)

The flow rate through the gap formed by the projection on the sleeve and the recesses of the screw

$$q_i(\Delta p_{out}) = \mu\operatorname{Re}\left[\frac{A_k}{2} + \delta R_k\right]\sqrt{2g\left(\frac{p_{out} - p_{in}}{\rho g} + h_d + l_{sr}\right)},$$  

(5)

where $p_{out}$, $p_{in}$ are the outlet and inlet pressures of the LSP respectively; $b$ is the width of the screw projections; $l_{sr}$ is the screw length; $\delta$ is the gap between the screw and the sleeve; $\rho$ is the density of fluid; $g$ is the gravitational acceleration; $h_d$ is the head losses in the gap formed by the projection on the sleeve and the recesses of the screw

$$h_d = \left(\lambda(\operatorname{Re})\frac{L_k}{4R_k} + \sum K\right)\frac{v_{avg, out}^2}{2g},$$  

(6)

where $v_{avg, out}$ is the average velocity in the screw channel at the pump outlet; $\mu(\operatorname{Re})$ and $\lambda(\operatorname{Re})$ are the coefficient of discharge through the gap formed by the projection on the sleeve and the recesses of the screw and the friction factor, which depend on the Reynolds number of flow $\operatorname{Re}$ [29, 30]; $\sum K$ is the sum of the head loss coefficients [30].
In formula (6), before the friction factor for the advanced LSP was put a coefficient $\frac{1}{D_i}$ that takes into account the LSP channels doidicity.

To calculate the flow characteristics of LSP, the geometry parameters of the pump operating elements, the parameters of the working fluid and the speed of the screw were pre-set. In the first stage of the calculation was determined the flow rate $q_i(n)$.

In the second stage was set the flow rate $q_i(\Delta \rho_{out})$. The flow rate $q_i(\Delta \rho_{out})$ should not exceed the flow rate $q_i(n)$. The formula (1) found the average flow rate at the pump outlet and the formula (6) the average speed of the working fluid in the screw channel at the outlet of the pump.

In the third stage, the Reynolds number of flow $Re$, $\lambda(Re)$, $\mu(Re)$, $h_o$ were calculated by the average velocity the screw outlet at the outlet of the pump [31-35].

In the fourth step, $\Delta \rho_{out}$ was calculated using (5):

$$\Delta \rho_{out} = \frac{q_i(\Delta \rho_{out})^2 \rho}{2\mu(Re)^2[0.5A_i + \delta R_i]} - \rho g(h_o + l_{nr}) .$$

(7)

It was assumed that the pump inlet pressure $p_{in} = 0$. Head $H$ at the pump outlet

$$H = \frac{\Delta \rho_{out}}{\rho g} .$$

(8)

Knowing $q_{avg}$ and $H$, the flow rate point of the characteristic was obtained. Next, a new flow rate $q_i(\Delta \rho_{out})$ was set, stages two through four were repeated, and a new flow rate point of the characteristic was found. The calculation was repeated to obtain the required number of points for flow rate characteristic (Fig. 5). The maximum pressure at the outlet of the pump is at $q_i(n) = q_i(\Delta \rho_{out})$.

![Figure 5. Characteristic curve of LSP.](image)

When calculating the flow characteristics of LSP parameters were assumed: the velocity on the walls, due to its sticking, is equal to zero; the working fluid has a density of $\rho = 920$ kg/m$^3$, a viscosity of $\eta = 25 \times 10^{-6}$ m$^2$/s, a temperature of $T = 353$ K; air content of 0.8% [31-35].

The movable operating elements of the pump have the following dimensions: the sleeve with a nominal internal diameter – 62 mm, pitch of one screw – 112 mm, cutting left; screw with an external diameter of 61 mm, pitch of cutting one screw – 112 mm, $z = 10$, $l_{scr} = 112$ mm, cutting left; screw grooves have a radial gap between the sleeve and the screw – 0.5 mm; $R_s = 2.25$ mm; cutting angle related to screw axis 70°. The speed of the screw $n = 2900$ rev/min. The location of the pump is vertical.
The developed design of LSP allows increasing the pump flow rate by almost 10%. At the same time the flow rate of LSP increases its hydraulic power $P = q_{av} \Delta p_{av}$.

Experimental studies have been conducted for 7 different typical LSPs. The discrepancy between the characteristic obtained experimentally and calculated for LSP with typical operating elements is no more than 13.7%. Thus, the feasibility of using in the industry developed LSP with operating elements of the improved form are proved.

5. Conclusion
Using the concept of reducing hydraulic resistance in the flow of the working fluid in the direct flow and increasing in the reverse flow (increase the diodicity), a new design of LSP operating elements was developed. By modeling the flow in LSP with different position of the screw relative to the fixed sleeve, the effectiveness of the proposed concept of improving the flow channel was proved. The analysis of the calculated flow rate characteristics of the typical and improved LSP proved the efficiency of application in the industry of improved design. The adequacy of the calculated flow rate characteristic was proved by comparison with the experiment, and the difference between the calculation and the experiment did not exceed 13.7%.

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