Improving the efficiency of the operating process of high specific speed torque-flow pumps by upgrading the flowing part design

V Y Kondus¹, R V Puzik¹, V F German¹, V O Panchenko¹, S M Yakhnenko²

¹ Department of Applied Hydro- and Aeromechanics, Sumy State University,
2, Ryms’kogo-Korsakova, Sumy 40007, Ukraine
² Processes and Equipment of Chemical and Petroleum-Refineries Department,
Sumy State University, 2, Ryms’kogo-Korsakova, Sumy 40007, Ukraine

E-mail: vladislav.kondus@meta.ua

Abstract. The article is devoted to the research of the torque-flow pump operating process. Its work is closely connected to the formation and stable functioning of the toroidal vortex. The theoretical bases of the formation of a toroidal vortex and the process of energy transfer in a torque-flow pump are considered in the research (vane and vortex components of the operating process). The fact of the presence of some additional hydraulic losses due to the mismatch of the location of the toroidal vortex center and the impeller blade edges has been established. The urgency of the paper is increasing the efficiency of torque-flow pump by improving its flowing part. The upgrade of the pump consists of the theoretical justification and practical implementation of the reduction of these additional hydraulic losses. In this aspect, the location of the impeller blade edge is aligned with the toroidal vortex center. The research was performed by conducting a numerical investigation. The calculations of a high specific speed torque-flow pump of three different design configurations of the impeller blades were performed. Practically confirmed increasing of the head (by 3.2 m) and efficiency (by 7-8%) of the pump with the second design of the impeller blades.

1. Introduction
Most of production processes are closely related to the transportation of liquids using pumping equipment. Generally, as the operating fluids are used untreated liquid containing inclusions.

When transporting liquids with the presence of inclusions, dynamic torque-flow pumps were acquired widespread (Fig. 1).

The torque-flow pump flowing part consists of a housing containing suction and discharge nozzles as well as a half-opened impeller.

Due to the wide passage channel of this pumps type, they can be effectively used to transport liquids with various types of inclusions (solid, fibrous, abrasive particles, etc.), high air or gas content, high viscosity, etc.

The main imperfection of torque-flow pumps is their low efficiency. However, when transporting liquids with inclusions (solid, abrasive, etc.), the costs of servicing, auditing, and repairing of torque-flow pumps are much lower than using centrifugal pumps. As a result, the total pump installation life...
cycle cost using torque-flow pumps in this case is lower than using centrifugal pumps [1]. Therefore, their using is a priority.

Figure 1. Torque-flow pump.

The research urgency is to identify ways to improve torque-flow pumps in order to improve their operating process efficiency while ensuring minimal investment costs, as well as the cost of maintenance of the pumping installation.

That means a comprehensive approach to improve the torque-flow pump. This will minimize total costs over the entire pump installation life cycle.

2. Analysis of published data and statement of research issue

Increasing of the torque-flow pump head can be achieved by performing winglets at the edges of the impeller blades in the direction of the operating side or backside of the blade [2]. However, to increase the pump head, it is necessary to have a slightly larger gap (15 mm or more) between the impeller and the cylindrical surface of the pump housing [3]. The installed effect can be ensured by simply increasing the impeller diameter by a given value.

A qualitative assessment of the influence of the structural elements of the torque-flow pumps flowing part on their characteristics is given in [4]. However, the paper does not provide recommendations for the designing of torque-flow pump flowing parts.

Improved design of the torque-flow pump housing, allows increasing its efficiency up to 4-5% [5]. However, ensuring the improvement of embedded pumps, the replacement of a valuable element, the pump housing, is thus required. This leads to significant investment costs.

In studies [6, 7] authors proposed to make improvements by replacing impellers with straight blades by similar impellers with curvilinear blades profile. Guidelines for the designing of such impellers are given in [8].

A qualitative picture of the fluid flow in the torque-flow pump flowing part is given in [9]. However, the absence of a mathematical model makes it impossible to develop recommendations for the designing of the pump flowing parts.

In the research [10], theoretically achievable efficiency of the "Turo"-type torque-flow pump operating process was determined based on the laws of energy conservation and moment of motion. It does not exceeding 60-62%. Based on this, the efficiency of the torque-flow pump of this type may not exceed 58%. It established that the toroidal vortex passes through the impeller intervane channels cyclically (2-3 times) [11]. Thus, the flow through the impeller is 2-3 times higher than the flow of the pump.

The literature review suggests that the torque-flow pump operating process is insufficiently studied. In particular, the location effect of the center of the toroidal vortex (in the free chamber, at the edge of the impeller blades or in impeller intervane channels) on the hydraulic losses in the torque-flow pump flowing part is currently unknown. The research in this direction of the operating process of the torque-flow pump with high specific speed \( n_s \) is considered promising. In this case, the free chamber has a width \( B \) much larger than the width of the blade impeller \( b_2 \). This allows the location of the
center of the toroidal vortex to be significantly affected by moving of the impeller blade edge into the free chamber.

3. The purpose and objectives of the research
The purpose of the research is to improve the efficiency of a torque-flow pump with high specific speed \( n_s \) by improving the design of its flowing part.

To achieve this goal, the main tasks are defined:
- theoretical substantiation of the possibility of efficiency increasing of the operating process of a torque-flow pump flowing part with high specific speed;
- identification of the main ways of increasing the efficiency of torque-flow pumps;
- researching of the influence of the torque-flow pump advanced design on its characteristics by performing a numerical investigation.

4. Theoretical basis of the research
The operating process of a torque-flow pump (Fig. 2) is characterized by the complex nature of energy transfer in its flowing part [8, 10].

**Figure 2.** Torque-flow pump operating process: \( Q_t \) – flow coming from the impeller directly to the pump outlet (through-flow); \( Q_s \) – flow that does not interact with blades impeller (flowing stream); \( Q_v \) – toroidal vortex.

In the first stage, it is similar to the operating process of a centrifugal pump. Energy is transferred to the fluid flow by its force interaction with the impeller blades. Thus, in the centrifugal pump, the fluid from the impeller intervane channels discharge directly to the discharge nozzle. In contrast, in a torque-flow pump, only a portion of the fluid \( Q_t \) enters the discharge nozzle from the impeller intervane channels. The other part \( (Q_v) \) forms a vortex flow (toroidal vortex) circulating in the pump flowing part. In this case, toroidal vortex acts as a "liquid blade". It transmits energy to a portion of the flow \( (Q_s) \) that does not interact with the blades (flowing stream). Thus, the flowing stream flows from the suction nozzle to the discharge nozzle without interacting with the impeller blades.

The research [8] propose a calculation model of a torque-flow pump operating process. It establish that its main components are blade and vortex operating processes. It determine the percent composition in each of them. It calculate the theoretically achievable efficiency of a torque-flow pump. However, the proposed design model is valid only if the width of the free chamber of the housing \( B \) is equal to the width of the impeller blades \( b_2 \). The impeller is in the cylindrical recess of the housing.

In case of the width of the impeller \( b_2 \) is larger than the width of the pump free chamber, the center of the toroidal vortex locates in the impeller intervane channels. This design characterize torque-flow pumps with low specific speed \( n_s \), which is determined by the dependence:
\[ n_s = \frac{n\sqrt{Q}}{H^{3/4}} \]  

(1)

where \( n \) – the rotation frequency of the pump shaft, rpm, \( Q \) – the pump supply, m³/h, \( H \) – the pump head, m

The part of the blade operating process of the pump increases, and the part of vortex operating process decreases. Since theoretically achievable efficiency blade operating process is equal to 1, and vortex operating process is equal to 0.5 [8], then the total pump efficiency is slightly higher.

It should be noted that the blades slightly deform the shape of the toroidal vortex as follows (Fig. 3).

**Figure 3.** Features of the structure of a toroidal vortex of low specific speed torque-flow pumps: thin line - vortex trajectory without hydraulic losses, thick line - real vortex trajectory.

The center of the toroidal vortex locates in the impeller intervane channels. The fluid tries to move from the periphery to the center in the range from the center of the toroidal vortex to the edge of the impeller blade. However, due to the force interaction with the blades at this intervane channels, it is reversed from the center to the periphery. As a result, some additional hydraulic losses occur.

For design of high specific speed vortex pumps, the width of the free chamber \( B \) is larger than the width of the impeller \( b_2 \) (Fig. 4).

In this case, the vortex part of the pump operating process increases and the blade part decreases accordingly. Since theoretically achievable efficiency blade operating process is equal to 1, and vortex operating process is equal to 0.5 [8], then the total pump efficiency is slightly lower.

In this case, the center of the toroidal vortex locates in the pump free chamber. The toroidal vortex deform as follows. In the range from the edge of the blade to the center of the toroidal vortex, the fluid interacts with the flow. In this case, the toroidal vortex transmits some energy to the flowing stream. As a result, the energy of the toroidal vortex decreases and its shape deviates from the circular. In the given range, there are some additional hydraulic losses, which somewhat reduce the overall efficiency of torque-flow pump.
5. Results of the research of the torque-flow pump operating process

5.1. Improving the efficiency of a torque-flow pump by improving its flowing part

Improvement of the flowing part of torque-flow pumps is advisable to achieve with the minimum life cycle costs of the pumping unit [1]. It means maximizing the efficiency of the pump operating process while ensuring the minimum operating, audit and repair costs of the pump unit. It should be noted that the minimal investment costs for upgrading the installed pumps also significantly reduce the overall cost of its life cycle. In practice, this means the need of minimal structural changes to the elements of the pumps flowing part. Such a design solution will provide minimal investment costs of the development and manufacture of model equipment for casting improved elements of the flowing part.

In this case, we propose to improve the flowing part by increasing the width of the impeller blade of the pump (Fig. 5).

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**Figure 4.** Features of the structure of a toroidal vortex of high specific speed torque-flow pumps: thin line - vortex trajectory without hydraulic losses, thick line - real vortex trajectory.

**Figure 5.** Features of the toroidal vortex structure of a torque-flow pump with high specific speed ns of the advanced flowing part design.
Increasing the width allows you to move a part of the blade into a free chamber. As a result, it is possible to coordinate the location of the center of the toroidal vortex directly at the edge of the impeller blade.

This design minimizes additional hydraulic losses because of eliminating mismatch of the vortex center and the location of the impeller blade edge. In this case the deformation of the vortex at the outlet of the impeller does not occur.

In general, the toroidal vortex should be considered as a component of two vortices [11]: longitudinal and transverse. The longitudinal vortex is discussed in Figures 3 - 5. It receives energy gain due to the force interaction with the impeller blades and transmits it to the flowing stream.

The transverse vortex transmits only a small fraction of the flow energy. However, it serves to increase its circumferential velocity $u_v$. It increases the cyclicity of the toroidal vortex.

The vortex center in pumps with high specific speed $ns$ locates at some distance from the edge of the blade. As a result, deformation of the transverse vortex occurs (Fig. 6). Therefore, the circumferential velocity $u_v$ decreases. This leads to decreasing in the cyclicity of the toroidal vortex. Thus, the energy transmitted to the flow stream decreases, which leads to decreasing of the pump efficiency.

The proposed design of the flowing part allows coordinating the location of the center of a transverse vortex with the location of the edge of the impeller blades (Fig. 7).

![Image](image_url)

**Figure 6.** Features of the transverse vortex structure of a high specific speed torque-flow pumps: thin line - vortex trajectory without hydraulic losses, thick line - real vortex trajectory.

The circumferential velocity of the transverse vortex increases compared to the previous version of constructive execution. It allows you to reduce hydraulic losses and increase the cyclicity of the vortex. As a result, the energy transmitted to the flowing stream is slightly higher.
5.2. *Methods of experimental research*

The experimental research was performed by conducting a numerical investigation using Ansys CFX software. Flowing parts of standard and advanced construction were tested (Fig. 8). The design parameters of the pump are: flow rate \( Q = 500 \text{ m}^3/\text{h} \), head \( H = 42 \text{ m} \), rotation frequency \( 1500 \text{ rpm} \).

Working medium - water at 25°C. The mode of operation is turbulent. For the closure of the Reynolds equations, we used a standard k-\( \varepsilon \) turbulence model. It corresponds to the results of real bench tests with sufficient accuracy [12].

The calculation area consists of two parts: the stator - housing, and the rotor - impeller. We constructed unstructured calculation grid for each part. The total number of cells in the calculation area is 1 million 500 thousand cells.

We made the calculation in a stationary formulation.
As a boundary condition at the inlet from the calculation area was flow rate through the flowing part of the torque-flow pump. A numerical investigation was carried out to construct the characteristics of the pump with the supply of the pump in the range from 0.05 to 1.4 $Q_{opt}$.

A pressure equal to 1 MPa was set as the boundary condition at the outlet of the pump. Due to the possibility of backflows at the outlet of the calculation area, the boundary condition "Opening" was set.

The convergence of the numerical investigation results was achieved by conducting a study with the task of interaction between the calculation areas "Frozen rotor". Data refinement was performed during the numerical investigation with carrying out of the interface of interaction between calculation areas "Stage". The results of the previous study were used as initial approximations.

5.3. Discussion of the numerical investigation results

According to the results of the research, the characteristics (Fig. 9) of the tested torque-flow pump of active (red) and advanced (blue) design were constructed.

![Characteristics of the torque-flow pump](image)

**Figure 9.** Characteristics of the torque-flow pump of active (solid line) and advanced (dashed line) design.

The design improvement made it possible to increase the efficiency of the torque-flow vortex pump in the optimal mode by 8-9%. The head pressure was increased by 3.2 m. The position of the best efficiency point (BEP) was moved to 80-85% (400-425 m$^3$/h) from the calculated position.

The achieved results can be explained as follows.

Firstly, in accordance with the theoretical data presented in the paper, the deformation of the toroidal vortex is reduced. The result is an increase of the efficiency of energy transfer in the vortex operating process.

Secondly, the insignificant exit of the impeller blade edge into the pump free chamber slightly increases the blade fraction and reduces the vortex fraction in the general vortex pump operating process (Fig. 10). It allows us to achieve some increase in head and efficiency of the pump.

![Torque-flow pump operating process](image)

**Figure 10.** Torque-flow pump operating process (B - free chamber width, B' - distance between the free chamber wall and the blade edge, $b_2$ - impeller blade width): a - existing design, b - advanced design.
The alignment of the center of the vortex and the impeller blade edge of the torque-flow pump is achieved only by a slight exit of the impeller into the pump free chamber. However, the wearing of the surface of the rotor element, the impeller, is negligible. Therefore, the increasing in maintenance and repair costs is negligible.

Subsequent moving of the impeller blade edge into the torque-flow pump free chamber (Fig. 11) leads to increasing of the blade fraction and to decreasing of the vortex fraction in the general torque-flow pump operating process. However, in this case, the center of the toroidal vortex locates in the intervane channels. It leads to the appearance of some additional hydraulic losses, which are similar to the case with a low specific speed torque-flow pump (Fig. 3).

According to the results of the numerical investigation (Fig. 12) of the flowing part of a torque-flow pump was installed the following. The BEP position has moved to 60-65% (300-325 m³/h) of the calculated position. The following operating parameters are reached at the BEP. Increasing of the efficiency achieved up to 4–5% relative to the existing design (but 3–4% less than the proposed one). The head is 5–6 m higher than the existing design (but 1.5–2 m lower than the proposed one). The received data refer to the flow rate mode of 300 m³/h (60% of submission of the calculated point). At the same time, it was determined in the calculating point that the pressure of such a pump is 4–5 m lower than of existing design pump (7–8 m lower than of the proposed one). Efficiency 2–2.5% lower than of the existing pump design (10–11% lower than of the proposed one).
Similar results were obtained in the research [13]. However, in this case, the moving of the impeller blade edges were released into the free chamber only for two of ten impeller blades. The study achieved increasing of the head up to 9% and of the efficiency up to 4%.

According to the obtained results, we can state the following. Some moving of the impeller blade edge into the free chamber leads to increasing in the proportion of the blade and reducing in the proportion of the vortex in the overall operating process of the torque-flow pump. The alignment of the distance from the housing free chamber wall to the impeller blade edge with the width of the impeller blade leads to minimization of deformation of the toroidal vortex (Fig. 7). Thus, increasing of the torque-flow pump efficiency is achieved with a minimum moving of the BEP position (15–20% of the calculating point position in the direction of flow rate reduction). Subsequent moving of the impeller blade edge into the pump free chamber results in a significant moving of the BEP (up to 35-40% of the calculation point position in the direction of flow rate reduction). At the BEP for such a design, there is some increase in head and efficiency. However, due to its significant moving to the direction of flow rate reduction, this effect is absent in the calculating point.

In the proposed design of the flowing part, most solids (including abrasives) flow in the flowing stream. Further moving of the impeller blade edge into the pump free chamber results in a significant moving of the BEP (up to 35-40% of the calculation point position in the direction of flow rate reduction). At the BEP for such a design, there is some increase in head and efficiency. However, due to its significant moving to the direction of flow rate reduction, this effect is absent in the calculating point.

In the proposed design of the flowing part, most solids (including abrasives) flow in the flowing stream. Further moving of the impeller blade edge into the free chamber of the pump, much larger part of inclusions will pass through its inte‌vene channels. This is a cause of much more intensive wearing of the surfaces of the rotational element, - the impeller. Thus, maintenance and repair costs also increase. Therefore, further moving of the impeller blade edge into the pump free chamber from the point of view of the total cost of the pump installation life cycle seems inappropriate.

In addition, further moving of the impeller blade edge into the pump free chamber reduces the maximum size of the permissible inclusions in the pumped liquid. It is usually permissible to transport liquids with inclusions up to 0.8 width of the pump free chamber B. The diameter of admissible inclusions during the operation of the torque-flow pumps with some movement of the impeller blade edge in the pump free chamber is determined by:

\[ D_{in} = 0.8B', \]  

where, B' - the distance between the impeller blade edge and the opposite housing free chamber wall

Thus, with a slight movement of the impeller blade edge into the pump free chamber, the maximum diameter of inclusions is reduced slightly.

With the further movement of the impeller blade edge into the pump free chamber, the size of maximum inclusions will be only 0.4 width of the pump free chamber B.

6. Conclusions
1. The paper deals with the high specific speed torque-flow pump. Theoretical aspects of the formation of a toroidal vortex are determined. The deformation conditions of its components (longitudinal vortex, transverse vortex) in the pump flowing part are determined. It is hypothesized that the alignment of the position of the center of the toroidal vortex and the position of the impeller blade edge reduces the vortex deformation, as well as additional hydraulic losses caused by it.

2. Improved torque-flow pump flowing part is developed. The parameters of the pump are: flow rate - \( Q = 500 \text{ m}^3/\text{h} \), head - \( H = 42 \text{ m} \), rotation frequency - 1500 rpm. The position of the blade edge of the pump impeller is slightly moved into the free chamber to align its position with the position of the center of the toroidal vortex in accordance to the hypothesis.

3. By carrying out the numerical investigation, it was increased the head (by 3.2 m) and the efficiency (by 8-9%) of the torque-flow pump with improved flowing part compared to the existing one. At the same time, the position of the best efficiency point (BEP) of the pump has moved for 15-20% in the direction of reducing of the flow rate. This result is achieved by reducing the deformation of the toroidal vortex. This reduces hydraulic losses in the flowing part of the pump. The result was also partly due to increasing of the blade fraction and decreasing of the vortex fraction of the overall...
torque-flow pump operating process. In general, it can be argued that the hypothesis is confirmed because of numerical investigation.

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