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EU REGULATORY APPROACHES TO THE ASSESSMENT OF ENERGY EFFICIENCY OF PUMPS AND THEIR APPLICABILITY TO TORQUE-FLOW CONSTRUCTIONS

КІЛЬКІСНИЙ АНАЛІЗ НОРМАТИВНИХ ПІДХОДІВ ЄС ДО ОЦІНЮВАННЯ ЕНЕРГОЕФЕКТИВНОСТІ НАСОСІВ ТА ЇХ ЗАСТОСОВНІСТЬ ДО ВІЛЬНОВИХРОВИХ КОНСТРУКЦІЙ

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Abstract. This paper investigates the applicability of the current European minimum energy efficiency criterion, the Minimum Efficiency Index (MEI), to torque-flow pumps, taking into account the physical limitations of their operating process. The research methodology is based on a regulatory and analytical assessment of ecodesign requirements for water pumps combined with analytical prediction of the achievable efficiency of torque-flow pumps. Using a formalized relationship for determining the minimum required hydraulic efficiency at the best efficiency point (BEP), the normative efficiency values were calculated for characteristic ranges of specific speed and flow rate. It is shown that even the minimum level of $MEI = 0.4$ imposes efficiency requirements in the range of 54–75%, while the predicted efficiency of torque-flow pumps is approximately 47–52%. A regulatory energy efficiency deficit of 3–28 percentage points is quantitatively established. The obtained results are consistent with analytical estimates of the physically achievable efficiency limit of the vortex working process, which does not exceed 66.6%. The study concludes that the existing energy efficiency assessment criteria require adaptation for pumps with vortex-dominated operating processes.

Keywords: torque-flow pump, energy efficiency, Minimum Efficiency Index (MEI), ecodesign, efficiency.

Problem Statement.

Improving the energy efficiency of pumping equipment is one of the key priorities of the current industrial policy of the European Union and is implemented through a system of ecodesign requirements and technical regulation. For dynamic water pumps, the primary quantitative energy efficiency criterion used in EU regulatory practice is the Minimum Efficiency Index (MEI) [1], which serves to establish the limiting values of permissible hydraulic efficiency of products.

At the same time, the existing regulatory framework, in particular Commission Regulation (EU) No 547/2012 [2] and the associated harmonized standards, has been developed with regard to the design and hydrodynamic characteristics of conventional dynamic pumps operating within a relatively narrow range of specific speed and characterized by high maximum efficiency. Torque-flow pumps (Fig. 1), which are widely used for pumping contaminated, abrasive, and gas-laden fluids [3], are characterized by a fundamentally different operating process, a significant contribution of recirculation zones [4], and increased hydraulic losses. These features substantially complicate the direct application of MEI-based criteria to this pump type.

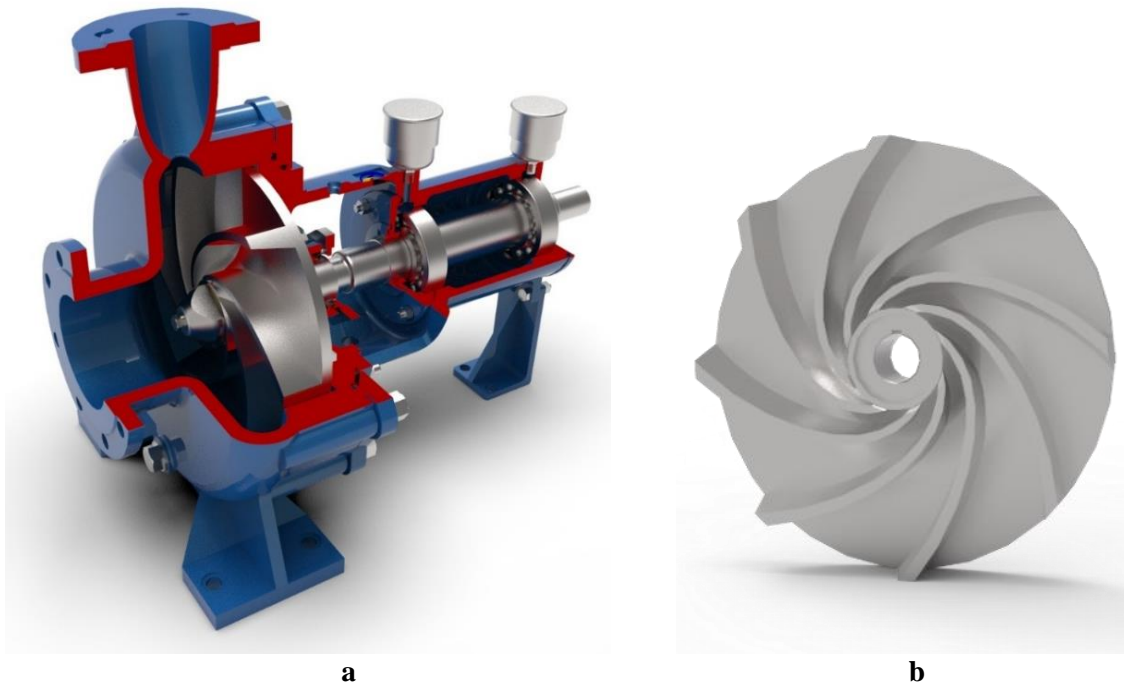


Fig. 1. Structural design: (a) torque-flow pump; (b) semi-open impeller of a torque-flow pump

In engineering practice, this leads to a regulatory inconsistency in which the energy efficiency of torque-flow pumps is assessed using criteria that are not adapted to their physical operating principles and real operating conditions. Such an approach complicates the justification of the energy feasibility of torque-flow pump applications [5] and creates barriers to their integration into the modern ecodesign regulatory framework.

In this context, the analysis of the applicability of current European regulatory energy efficiency criteria to torque-flow pumps and the identification of possible directions for their improvement, taking into account the specific features of the hydrodynamic process, constitute a relevant and timely research problem.

Analysis of Recent Research.

The issue of improving the energy efficiency of pumping equipment has been actively addressed over the past decade in scientific and regulatory–methodological studies [6,7], focusing on the development of unified assessment criteria and the harmonization of technical requirements. A key development in this field has been the implementation of the ecodesign framework in the European Union, within which the Minimum Efficiency Index (MEI) for dynamic water pumps was introduced and formalized in Commission Regulation (EU) No 547/2012 and the associated harmonized standards.

Scientific publications and reports of industry associations indicate that the application of the MEI criterion has significantly increased the average hydraulic efficiency of serial pumps of conventional designs and has stimulated manufacturers to optimize the geometry of the flow passages and impellers [8]. At the same time, it is noted that the methodology for determining MEI is based on assumptions typical of pumps with relatively high efficiency and a clearly defined best efficiency point (BEP) [9].

A number of studies devoted to a system-based approach to energy efficiency assessment emphasize the limitations of using nameplate efficiency values for pumps operating over a wide range of conditions or under non-standard hydraulic regimes [10–11]. In this context, the Extended Product Approach has been proposed, which involves evaluating the efficiency of a pump unit as part of a system including the electric drive and control devices.

At the same time, an analysis of available publications shows that the majority of studies are focused on pumps of traditional dynamic designs, while specialized pump types, in

particular torque-flow pumps, remain largely outside the scope of regulatory and methodological developments [12]. The specific features of their operating process, associated with the formation of recirculation zones and a free vortex, lead to a significant reduction in hydraulic efficiency when assessed using classical criteria [13], which complicates the correct application of the MEI index.

Thus, the analysis of recent research demonstrates that, despite significant progress in the regulatory framework for the energy efficiency of pumping equipment, the issue of adapting existing European assessment criteria to torque-flow pumps remains insufficiently addressed and requires further scientific investigation.

Research Methodology.

The purpose of this study is to analyze the applicability of the existing European regulatory energy efficiency criteria to torque-flow pumps and to identify the limitations of their use taking into account the specific features of the operating process. To achieve this purpose, the following research tasks were addressed:

1. To analyze the current European regulatory approaches to the energy efficiency assessment of dynamic pumps, in particular the Minimum Efficiency Index (MEI), and to identify the hydrodynamic assumptions underlying these approaches.

2. To perform a regulatory and calculation-based assessment of the minimum required efficiency of torque-flow pumps at the best efficiency point (BEP) according to the MEI criterion for characteristic values of specific speed and flow rate.

3. To evaluate the physically achievable level of energy efficiency of torque-flow pumps based on analytical efficiency relationships and to determine the limits of maximum development of the vortex working process.

4. To compare the minimum required and predicted efficiency values of torque-flow pumps within a representative parameter range and to quantitatively determine the energy efficiency deficit.

5. To analyze the influence of specific speed and flow rate on the magnitude of the regulatory efficiency deficit and to identify parameter regions in which compliance with the MEI requirements is fundamentally limited.

6. To substantiate the need for adapting regulatory energy efficiency assessment criteria for pumps with vortex-dominated operating processes, taking into account their physical and operational characteristics.

7. To define directions for further research related to the development of adapted approaches to the energy efficiency assessment of torque-flow pumps and their verification using experimental and numerical methods.

To achieve the stated objectives, a regulatory and analytical approach was applied, combining the analysis of European Union regulatory documents with an engineering interpretation of the hydrodynamic characteristics of pumping equipment.

The research methodology is aimed at a quantitative verification of the applicability of the current European minimum energy efficiency criterion, the Minimum Efficiency Index (MEI), to torque-flow pumps, taking into account the physical limitations of their operating process. Unlike conventional centrifugal pumps, for which the hydrodynamic energy transfer mechanism theoretically allows achieving efficiency values close to 100%, torque-flow pumps are characterized by a fundamentally different energy conversion mechanism, which results in the existence of a limiting theoretically achievable efficiency level. Accordingly, the methodology is based on a combination of regulatory and calculation-based analysis of ecodesign requirements for water pumps and analytical prediction of the achievable efficiency of torque-flow pumps.

In the first stage, the provisions of Commission Regulation (EU) No 547/2012 and the corresponding Technical Regulation of Ukraine were applied, according to which the minimum permissible hydraulic efficiency of pumps is determined using the MEI. For

dynamic pumps, the minimum required efficiency at the best efficiency point (BEP) is defined by the analytical relationship:

$$(\eta_{BEP})_{\min.regu} = 88.59x + 13.46y - 11.48x^2 - 0.85y^2 - 0.38x \cdot y - C_{PumpType.rpm} \quad (1)$$

where $x = \ln(n_s)$ is the natural logarithm of the specific speed, $y = \ln(Q)$ is the natural logarithm of the pump flow rate, m^3/h , $C_{PumpType.rpm}$ is a regulatory constant depending on the pump type, rotational speed, and MEI level.

The minimum permissible hydraulic efficiency values at characteristic part-load and overload operating points are determined by the following relationships:

$$(\eta_{PL})_{\min.regu} = 0.947 \cdot (\eta_{BEP})_{\min.regu} ; \quad (2)$$

$$(\eta_{OL})_{\min.regu} = 0.947 \cdot (\eta_{BEP})_{\min.regu} . \quad (3)$$

Since the current regulatory documents do not define a separate category for torque-flow pumps, the tabulated value $C=130.27$, corresponding to ESOB-type pumps operating at a rotational speed of 2900 rpm with $MEI = 0.4$, was used as a reference regulatory constraint for comparative analysis.

In the second stage of the methodology, the results of analytical prediction of the efficiency of torque-flow pumps were employed. According to analytical models, the maximum theoretically achievable efficiency of the vortex working process is $\eta_{OP,max} = 0,666$ at $n_s \approx 100$.

For real torque-flow pumps, the overall predicted efficiency $\eta_{TFP}(n_s)$ [14] is defined as a function of specific speed and exhibits a maximum within the range $70 \leq n_s \leq 140$, which corresponds to the optimal development of the vortex mechanism [15].

A comparison of the minimum required efficiency values calculated using the MEI-based formulation with the predicted values of $\eta_{TFP}(n_s)$ enables a quantitative assessment of the regulatory efficiency deficit and allows the applicability limits of the MEI criterion for torque-flow pumps to be established.

Research Results.

The conducted analysis showed that the methodology for determining the Minimum Efficiency Index (MEI), established in the current regulatory documents of the European Union, has been developed with regard to the hydrodynamic characteristics of pumps of traditional dynamic designs. It is based on the assumption of a clearly defined best efficiency point (BEP) and a relatively uniform distribution of losses over the operating range. For torque-flow pumps, these assumptions are only partially satisfied.

It was established that a characteristic feature of torque-flow pumps is a significant share of energy expended on the formation and maintenance of the free vortex zone and recirculation flows. This leads to a shift of the maximum hydraulic efficiency and to flatter head–flow characteristics compared to classical centrifugal pumps. As a result, the efficiency value at the BEP does not adequately reflect the actual energy efficiency of a torque-flow pump over a wide range of operating conditions.

Table 1 presents the results of calculating the minimum required efficiency at the BEP according to the MEI criterion for characteristic values of specific speed and flow rate.

The obtained values demonstrate that even the minimum regulatory level $MEI = 0.4$ imposes energy efficiency requirements on torque-flow pumps in the range $(\eta_{BEP})_{\min,requ} = 54\text{--}75\%$, depending on the flow rate and specific speed.

Based on the analytical prediction of the efficiency of torque-flow pumps, characteristic efficiency values $\eta_{TFP}(n_s)$ in the optimal operating region were obtained (see Table 2).

Taking into account the data presented in Tables 1 and 2, it is demonstrated that even within the range of maximum achievable efficiency of the torque-flow pump operating

process, the predicted efficiency values are significantly lower than the minimum required values obtained according to the MEI criterion.

Table 1. Minimum required efficiency $(\eta_{\text{BEP}})_{\text{min,requ}}$ of pumps at the BEP for MEI = 0.4

Pump specific speed, n_s	Pump Flow rate, Q , m ³ /h	Minimum required efficiency $(\eta_{\text{BEP}})_{\text{min,requ}}$, %
70	20	66.75
70	50	72.23
70	100	75.42
100	20	61.69
100	50	67.04
100	100	70.14
140	20	54.24
140	50	59.47
140	100	62.48

Table 2. Predicted efficiency of torque-flow pumps $\eta_{\text{TFP}}(n_s)$ in the specific speed range n_s from 70 to 140

Pump specific speed, n_s	Predicted efficiency $\eta_{\text{TFP}}(n_s)$
70	47.37
100	52.40
140	50.84

A comparison of the minimum required efficiency of pumps at the BEP, $(\eta_{\text{BEP}})_{\text{min,requ}}$ for MEI = 0.4 with the predicted efficiency values of torque-flow pumps $\eta_{\text{TFP}}(n_s)$ in the specific speed range n_s from 70 to 140 made it possible to determine the energy efficiency deficit $\Delta\eta$ (see Table 3).

The performed calculation-based analysis using the formulation for the minimum required efficiency at the best efficiency point, established within the MEI criterion, showed that even the minimum regulatory level MEI = 0.4 imposes requirements that are stringent for torque-flow pump designs. Within the specific speed range $n_s = 70 \dots 140$, corresponding to the optimal operating zone of torque-flow pumps, the calculated values of $(\eta_{\text{BEP}})_{\text{min,requ}}$ for characteristic flow rates $Q = 20 \dots 100$ m³/h fall within the range of 54–75%, whereas the predicted efficiency values of torque-flow pumps in the same parameter range amount to approximately 47–52%. Thus, a regulatory energy efficiency deficit of 3–28 percentage points is quantitatively established; moreover, even at $n_s \approx 100$ this deficit exceeds 10–15 percentage points for most operating flow rates.

Table 3. Energy efficiency deficit of torque-flow pumps for MEI = 0.4

Pump specific speed, n_s	Pump Flow rate, Q , m ³ /h	Energy efficiency deficit, $\Delta\eta$, %
70	20	19.38
70	50	24.86
70	100	28.05
100	20	9.29
100	50	14.64
100	100	17.74
140	20	3.40
140	50	8.63
140	100	11.64

The obtained results are consistent with analytical estimates of the physically achievable energy efficiency limit of torque-flow pumps. According to predictive relationships, the maximum theoretically possible efficiency of the vortex working process is limited to $\eta_{OP,max} \approx 66.6\%$ and can only be realized within a narrow range of specific speed. In contrast to centrifugal pumps, for which the efficiency can theoretically approach 100% in a limiting case, torque-flow pumps are subject to a fundamental physical limitation caused by the dominance of the vortex-based energy transfer mechanism. This limitation makes compliance with the MEI requirements impossible without accounting for this specific feature of the operating process.

In this context, the application of the MEI criterion to torque-flow pumps without considering the above-mentioned physical constraints leads to a systematic overestimation of regulatory energy efficiency requirements. Even the minimum level $MEI = 0.4$ can be achieved only for certain parameter combinations and typically requires a compromise with the functional properties of the pumps, in particular their ability to operate stably when handling contaminated and abrasive fluids.

Accordingly, the obtained results indicate the necessity of adapting the regulatory approach to the energy efficiency assessment of torque-flow pumps. Promising directions include the introduction of correction factors into the existing MEI methodology, the establishment of a separate category of pumps with vortex-dominated operating processes, or the application of a system-based assessment approach oriented toward real operating conditions rather than solely toward the best efficiency point.

It is further shown that the application of the MEI criterion to torque-flow pumps without accounting for the specifics of their operating process may lead to an underestimated assessment of their energy feasibility, especially in cases where such pumps are used for pumping fluids with a high content of solid particles or gas inclusions. Under these conditions, the operational efficiency of the pumping unit is determined not by the maximum efficiency value but by the stability of performance characteristics and the ability to operate without clogging or emergency regimes.

The analysis also demonstrated that the current regulatory approaches do not account for the influence of design parameters specific to torque-flow pumps, such as the geometry of the free vortex chamber, the toroidal vortex structure, and the relative clearance between the impeller and the casing, on the overall energy balance. This limits the applicability of the MEI index as an optimization tool for such pumps at the design stage.

The obtained results confirm the expediency of extending the existing energy efficiency assessment methodology through the introduction of correction factors or parametric relationships adapted to torque-flow pumps. Another promising direction is the application of a system-based approach, in which energy efficiency is evaluated for the pumping unit as part of a real hydraulic system, taking into account load regimes and operating conditions.

Conclusions.

The conducted analysis showed that the existing European regulatory approaches to the assessment of pump energy efficiency, based on the use of the Minimum Efficiency Index (MEI), have been developed with regard to the hydrodynamic characteristics of centrifugal pumps and do not account for the physical limitations of the operating process of torque-flow pumps.

Based on the regulatory and calculation-based analysis, it was established that even the minimum level $MEI = 0.4$ imposes requirements on the hydraulic efficiency at the best efficiency point (BEP) in the range of 54–75% for specific speed values $n_s = 70 \dots 140$ and flow rates $Q = 20 \dots 100 \text{ m}^3/\text{h}$, which correspond to the optimal operating range of torque-flow pumps.

According to the results of analytical prediction, the efficiency of torque-flow pumps within the specified specific speed range amounts to approximately 47–52%, while the

maximum theoretically achievable efficiency of the vortex working process is limited to $\eta_{OP,max} \approx 66.6\%$. This fundamentally distinguishes torque-flow pumps from centrifugal pumps.

It was quantitatively demonstrated that the deficit between the regulatory minimum required and the physically achievable energy efficiency levels of torque-flow pumps ranges from 3 to 28 percentage points, depending on the combination of n_s and Q . This excludes the possibility of eliminating the deficit solely through design optimization without compromising the functional properties of the pumps.

The obtained results indicate the necessity of adapting regulatory energy efficiency assessment criteria for pumps with vortex-dominated operating processes. In particular, this may involve the introduction of correction factors into the MEI methodology, the establishment of a separate pump category, or the application of a system-based approach oriented toward real operating conditions of pumping units.

Further research should be directed toward the development of adapted energy efficiency assessment criteria for torque-flow pumps, taking into account their operation as part of pumping systems, as well as toward experimental and CFD-based verification of the obtained analytical results.

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КІЛЬКІСНИЙ АНАЛІЗ НОРМАТИВНИХ ПІДХОДІВ ЄС ДО ОЦІНЮВАННЯ ЕНЕРГОЕФЕКТИВНОСТІ НАСОСІВ ТА ЇХ ЗАСТОСОВНІСТЬ ДО ВІЛЬНОВИХРОВИХ КОНСТРУКЦІЙ

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Анотація.

У роботі досліджено застосовність чинного європейського критерію мінімального індексу енергоефективності (Minimum Efficiency Index, MEI) до насосів вільновихрового типу з урахуванням фізичних обмежень їх робочого процесу. Методологія дослідження базується на нормативно-розрахунковому аналізі вимог екодизайну водяних насосів та аналітичному прогнозуванні досяжного коефіцієнта корисної дії вільновихрових насосів. На основі формалізованої залежності для визначення мінімально необхідної гідравлічної ефективності у точці найбільшої ефективності виконано розрахунок нормативних значень ККД для характерних діапазонів питомої швидкохідності та подачі. Показано, що навіть мінімальний рівень MEI = 0,4 формує вимоги до ефективності в межах 54–75 %, тоді як прогнозований ККД вільновихрових насосів становить приблизно 47–52 %. Кількісно встановлено нормативний дефіцит енергоефективності на рівні 3–28 відсоткових пунктів. Отримані результати узгоджуються з аналітичними оцінками фізично досяжної межі ефективності вихрового робочого процесу, що не перевищує 66,6 %. Зроблено висновок про необхідність адаптації критеріїв оцінювання енергоефективності для насосів з вихровим домінуванням робочого процесу.

Ключові слова: вільновихровий насос, енергоефективність, мінімальний індекс ефективності (MEI), екодизайн, коефіцієнт корисної дії.