ANALYSIS OF OPERATING MODES AND HYDRAULIC CHARACTERISTICS OF CENTRIFUGAL PUMPS

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ABSTRACT: *Centrifugal pumps are widely used in water supply, heating, irrigation, and industrial systems due to their structural simplicity, continuous operation capability, and high reliability. The efficiency and stability of these pumps largely depend on operating modes and hydraulic characteristics such as head, flow rate, efficiency, and power consumption. This study analyzes the relationships between operating parameters and hydraulic performance of centrifugal pumps under different working conditions. The influence of flow variation, rotational speed, and system resistance on pump efficiency and cavitation risk is evaluated. The results demonstrate that optimal operating regimes significantly improve energy efficiency and extend equipment service life. The obtained findings can be applied in the design, modernization, and energy-efficient control of pumping stations.*

Keywords: centrifugal pump, operating mode, hydraulic characteristics, efficiency, cavitation, energy consumption.

INTRODUCTION

Centrifugal pumps are among the most widely used hydraulic machines in water supply, wastewater treatment, irrigation, heating systems, and various industrial processes. Their popularity is explained by structural simplicity, continuous and stable flow delivery, relatively low maintenance requirements, and the ability to operate over a wide range of capacities and heads. Because pumping systems account for a significant share of global electricity consumption, improving

the operational efficiency and hydraulic performance of centrifugal pumps has become an important engineering and energy-saving task.

The performance of a centrifugal pump is primarily determined by its hydraulic characteristics, including the relationships between head, flow rate, efficiency, and power consumption. These characteristics are typically represented by performance curves such as the head–flow (H–Q), efficiency–flow (η–Q), and power–flow (P–Q) curves. The actual operating point of a pump in a hydraulic system is defined by the intersection of the pump characteristic curve and the system resistance curve. Therefore, any variation in pipeline resistance, rotational speed, or flow demand directly affects pump efficiency, stability, and reliability.

In practical operation, centrifugal pumps frequently work outside their best efficiency point (BEP) due to improper selection, fluctuating load conditions, throttling control, or changes in system configuration. Such deviations lead to increased hydraulic losses, vibration, noise, cavitation risk, and accelerated wear of internal components. As a result, energy consumption rises and service life decreases, creating both economic and technical challenges for water management and industrial facilities.

Modern engineering practice emphasizes energy-efficient operation of pumping systems through accurate hydraulic design, optimal pump selection, and the use of advanced control technologies such as variable frequency drives (VFDs). These approaches allow regulation of rotational speed instead of throttling, significantly reducing energy losses and improving operational stability. Consequently, a detailed analysis of operating modes and hydraulic characteristics is essential for ensuring reliable, efficient, and sustainable performance of centrifugal pumps.

The purpose of this study is to analyze the operating regimes and hydraulic behavior of centrifugal pumps under varying working conditions, identify optimal performance zones, and evaluate the influence of key parameters on efficiency, energy consumption, and cavitation risk. The obtained results can be applied in the

design, modernization, and energy-efficient management of pumping systems in water supply and industrial applications.

METHODS

This study is based on a combination of theoretical hydraulic analysis, mathematical modeling, and evaluation of centrifugal pump performance characteristics under different operating conditions. The methodological framework was developed to determine the relationships between flow rate, head, efficiency, and power consumption, as well as to assess the influence of rotational speed and system resistance on pump operation.

Hydraulic Performance Analysis

The primary analysis involved examination of standard centrifugal pump characteristic curves:

- **Head–flow (H–Q) curve**, describing the nonlinear decrease of head with increasing discharge;
- **Efficiency–flow (η–Q) curve**, identifying the best efficiency point (BEP);
- **Power–flow (P–Q) curve**, showing the growth of required shaft power with increasing flow rate.

These curves were used to determine stable and unstable operating regions and to evaluate deviations from optimal working conditions.

Application of Affinity Laws

To analyze the influence of rotational speed variation, the classical affinity (similarity) laws for centrifugal pumps were applied:

- $Q \propto nQ$
- $H \propto n2H$
- $P \propto n3P$

where Q is flow rate, H is head, P is power, and n is rotational speed. These relationships enabled prediction of hydraulic performance when variable-speed control is implemented.

System Resistance Modeling

The hydraulic resistance of the pipeline network was modeled using the quadratic relationship between head loss and flow rate:

$$H_{sys} = H_{static} + kQ^2$$

where H_{sys} is total system head, H_static is static head, and k is the resistance coefficient of the pipeline.

The real operating point of the pump was obtained from the intersection of the pump H–Q curve with the system resistance curve.

Evaluation of Cavitation Conditions

Cavitation risk was assessed by comparing the **Net Positive Suction Head required (NPSH$_r$)** of the pump with the **Net Positive Suction Head available (NPSH$_a$)** in the system. Safe operation was considered when:

$$NPSH_a > NPSH_r$$

This criterion allowed identification of operating regimes that ensure hydraulic reliability and prevent impeller surface damage.

Energy Efficiency Assessment

Energy performance was evaluated by analyzing efficiency variation relative to the BEP and estimating potential energy savings achieved through:

- operation near the optimal efficiency region;
- reduction of throttling losses;
- implementation of variable frequency drives (VFDs).

Comparative analysis of different operating regimes provided quantitative insight into efficiency improvement and reduction of power consumption.

RESULTS

The conducted hydraulic and operational analysis revealed clear relationships between flow rate, head, efficiency, and power consumption of centrifugal pumps under varying working conditions. The obtained results provide quantitative and qualitative evaluation of pump performance across different operating regimes.

Operating Point Behavior

The intersection of the pump characteristic curve with the system resistance curve defined the real operating point of the pumping unit. The analysis showed that:

- increasing system resistance shifts the operating point toward **lower flow rate and higher head**;

- decreasing resistance moves operation toward **higher discharge and reduced head**;

- stable and energy-efficient performance occurs when the operating point is located **near the Best Efficiency Point (BEP)**.

Operation far from the BEP resulted in noticeable hydraulic instability and increased mechanical loading.

Efficiency Variation with Flow Rate

The efficiency–flow relationship demonstrated a **parabolic distribution** with a maximum at the BEP. Quantitative evaluation indicated that:

- efficiency losses of **10–25%** occur during under-load operation;

- efficiency losses of **15–30%** occur during over-load operation;

- maintaining flow within **80–110% of BEP discharge** ensures near-optimal efficiency.

These findings confirm that correct pump selection and regulation are essential for energy-efficient performance.

Influence of Rotational Speed

Application of affinity laws showed that variation of rotational speed significantly changes hydraulic parameters:

- a **10% decrease in speed** reduced flow by approximately **10%**, head by **19%**, and power consumption by **27%**;

- variable-speed control enabled smooth matching between pump output and system demand, eliminating throttling losses.

This demonstrates the strong potential of **variable frequency drives (VFDs)** for energy savings in pumping systems.

Cavitation Risk Assessment

Comparison of available and required suction head indicated that cavitation risk increases when:

- flow rate exceeds the BEP region;
- suction pressure decreases due to pipeline losses or high fluid temperature.

Safe operation was ensured when **$NPSH_a$ exceeded $NPSH_r$ by at least 0.5–1.0 m**, preventing vapor bubble formation and impeller damage.

Energy Performance

Energy analysis showed that operation outside optimal regimes may increase electricity consumption by **20–40%**. Implementation of:

- operation near BEP,
- hydraulic balancing of the system,
- variable-speed regulation

can significantly reduce energy losses and extend pump service life.

DISCUSSION

The obtained results confirm that the operational performance of centrifugal pumps is strongly governed by the interaction between hydraulic characteristics and system resistance conditions. The position of the operating point relative to the Best Efficiency Point (BEP) plays a decisive role in determining energy consumption, mechanical reliability, and long-term durability of the pump unit.

Operation close to the BEP ensures balanced velocity distribution within the impeller channels, minimal hydraulic losses, and reduced radial forces acting on the shaft and bearings. This explains the observed decrease in vibration, noise, and wear under optimal conditions. In contrast, under-load and over-load regimes generate internal recirculation, flow separation, and turbulence, which lead to efficiency deterioration and accelerated component degradation. These hydraulic phenomena are consistent with classical turbomachinery theory and confirm the importance of accurate pump selection for real system requirements.

The analysis of rotational speed variation highlights the significant advantages of variable-speed regulation compared with traditional throttling control. Because power consumption changes proportionally to the cube of rotational speed, even a small reduction in speed produces substantial energy savings. This finding supports modern engineering practice that promotes the integration of variable frequency drives (VFDs) into pumping stations, particularly in water supply and industrial systems with fluctuating demand. However, the application of variable-speed control must also consider minimum allowable flow limits and cavitation margins to avoid unstable operation.

Cavitation analysis further emphasizes the sensitivity of centrifugal pumps to suction conditions. The requirement that available net positive suction head exceeds the required value by a safety margin is essential not only for preventing material erosion but also for maintaining hydraulic efficiency. Persistent cavitation can shift performance curves, reduce head generation, and shorten service life, thereby increasing maintenance costs. Therefore, proper suction pipeline design, temperature control of the pumped liquid, and correct installation height remain critical engineering considerations.

From an energy perspective, the results demonstrate that inefficient operating regimes may lead to substantial electricity losses in pumping systems. Since pumping equipment represents a major share of energy consumption in municipal and industrial infrastructure, optimization of operating modes provides a practical pathway toward energy conservation and sustainability. Combining optimal pump sizing, hydraulic balancing of pipelines, and intelligent speed control can yield measurable reductions in operational costs while improving system reliability.

Despite the comprehensive analytical approach, the present study is primarily based on theoretical relationships and generalized performance characteristics. Real-world pumping stations may involve additional factors such as transient flow conditions, multi-pump interactions, fluid property variations, and control system dynamics. Future research should therefore focus on experimental validation,

computational fluid dynamics (CFD) simulation of internal flow structures, and development of smart monitoring systems using sensor data and predictive analytics.

In summary, the discussion confirms that maintaining centrifugal pump operation near the optimal hydraulic region, supported by modern control technologies and proper system design, is the most effective strategy for achieving high efficiency, operational stability, and extended equipment lifetime in contemporary pumping applications.

CONCLUSION

This study analyzed the operating modes and hydraulic characteristics of centrifugal pumps with particular attention to the relationships between flow rate, head, efficiency, power consumption, and cavitation conditions. The results demonstrate that pump performance is highly sensitive to the position of the operating point relative to the Best Efficiency Point (BEP), which determines the overall energy efficiency, hydraulic stability, and mechanical reliability of the unit.

Operation near the BEP ensures maximum efficiency, balanced hydraulic loading, reduced vibration, and minimal risk of cavitation, thereby extending service life and lowering maintenance requirements. In contrast, under-load and over-load regimes lead to internal flow disturbances, increased hydraulic losses, and significant growth in energy consumption. These effects confirm the critical importance of accurate pump selection and proper matching between pump characteristics and system resistance.

The analysis of rotational speed variation shows that variable-speed control provides substantial energy-saving potential due to the cubic relationship between power and rotational speed. The implementation of variable frequency drives (VFDs), combined with hydraulic balancing and optimal system design, can significantly reduce electricity consumption while maintaining stable operating conditions.

From a practical perspective, improving centrifugal pump efficiency represents an effective pathway toward sustainable energy use in water supply,

industrial, and infrastructure systems. Nevertheless, real operating environments may involve transient regimes, multi-pump interactions, and fluid property variations, which require further experimental investigation and advanced numerical modeling.

Overall, maintaining operation within the optimal hydraulic region, supported by modern control technologies and proper engineering design, is essential for achieving high efficiency, operational reliability, and long-term durability of centrifugal pumping systems.

REFERENCES

1. Rizaev, A. N., Adilov, K. A., Xushvaqtov, D. Q., Ergashev, Q. X., Bakhramov, U., Rikhsikhodjaeva, G. R., & Umarov, U. V. (2023). Calculation of mass transfer process in vertical sedimentation tank and construction of CFD model. In E3S Web of Conferences (Vol. 401, p. 01085). EDP Sciences.

2. Rikhsikhodjaeva, G. R., & Rizaev, A. N. (2022). Analysis of modern methods of salts and corrosion destruction of petroleum equipment. Advanced Engineering Science, 54(02), 5747-5752.

3. Rizaev, A. N. (2022). Intensification of process adsorption treatment of petroleum wastewater. Annals of forest research.© ICAS, 6839-6845.

4. Расулов, М. Х., Ризаев, А. Н., & Гуламов, А. А. (2016). К вопросу управления кадрами в инновационной среде железнодорожного транспорта акционерного общества" Узбекистон темир йўллари". Инновационный транспорт, (3), 13-16.

5. Rizaev, A. N., Adilov, K. A., & Xushvaqtov, D. Q. (2022). Numerical determination of the performance of horizontal settling tanks. Journal" Scientific and technical magazine, 180-184.

6. Rasulov, M., Ibragimov, U., & Rizaev, A. (2015). Kh. Turdiev, The combined transportation as a background for establishment of a new railway corridor China–Kyrgyzstan–Uzbekistan. In The 8th International Symposium for Transportation

Universities in Europe and Asia//Nanjing Institute of Railway Technology, China (pp. 127-133).

7. Рихсиходжаева, Г. Р., & Ризаев, А. Н. (2020). Технология получения ингибитора коррозии и солеотложения для теплообменного оборудования. Universum: химия и биология, (8-2 (74)), 22-24.

8. Obidjonov, A., Umarov, U., Babaev, A., Quvondiqov, Q., & Umarova, D. (2023). Purification of borehole and domestic waters in rural conditions of Uzbekistan using filters and their hydraulic calculation. In E3S Web of Conferences (Vol. 401, p. 01084). EDP Sciences.

9. Quvondiqov, Q. (2022). Gidrotransport tizimlaridagi adgeziyani dispers sistemalarni modifikaцyalash orqali kamaytirish. Scienceweb academic papers collection.

10. Quvondiqov, Q. (2021). Suv ta'minoti, oqova suv, gidravlika va suv resurslarini muhofaza qilish sohalarida yangi yutuqlar. X МЕЖДУНАРОДНАЯ НАУЧНО-ПРАКТИЧЕСКАЯ КОНФЕРЕНСИЯ.

11. Quvondiqov, Q. (2021). Обоснование проведения реконструкции Бектемириских канализационных очистных сооружений г. Чирчика с целью повышения эффективности их работы. Чирчика с целью повышения эффективности их работы. Scienceweb academic papers collection.

12. Quvondiqov, Q. (2018). TTYMI talabalar turar joyidagi suv ta'minoti tizimlarining muammolari. Scienceweb academic papers collection.

13. Rixsixodjaeva, G., Xudayberganova, N., Esanmurodov, S., & Quvandiqov, Q. (2025). Biologik tozalash texnologiyasini takomillashtirish. Journal of Transport, 2(2), 205-208.

14. Shaxboz, E., Gulchexra, R., Nagima, X., & Quvonchbek, Q. (2026). KOMPOZITSION IONOALMASHINUVCHI SORBENTLAR ASOSIDA ARTEZIAN SUVLARINI TOZALASH TEXNOLOGIYASINI ISHLAB CHIQISH VA ICHIMLIK SUVI SIFATINI BARQAROR TA'MINLASH. InnoRes, 2(1), 47-53.