INTEGRATED CFD AND DIGITAL MODELING APPROACH FOR ENERGY-EFFICIENT OPERATION OF DEEP-WELL WATER SUPPLY SYSTEMS

Musajonov Mukhammadrasul
Ahmadjon Ibadullaev
Chorshanbiev Umar
Tashkent State Transport University, Temiryo'lchilar Street 1, Tashkent, 100167, Uzbekistan, (e-mail: muhammadrasulmusajonov@gmail.com, ibadullaev1957@bk.ru, umarttymikq25@gmail.com)
ORCID: 0009-0002-5613-5134, 0000-0002-8089-2592, 0000-0001-5268-3075.

Abstract: Deep-well water supply systems are characterized by significant hydraulic losses and high energy consumption, especially at depths exceeding 150–200 m. Traditional design and operational approaches often rely on simplified hydraulic calculations, which limit the potential for energy optimization. This paper presents an integrated approach combining Computational Fluid Dynamics (CFD) modeling and digital monitoring concepts to improve the energy efficiency of deep-well water supply systems. A three-dimensional CFD model of the well–pump–pipeline system was developed using ANSYS Fluent to analyze flow behavior, pressure distribution, and hydraulic losses under different operating conditions. The simulation results were used to evaluate pump power demand and identify optimal flow regimes with reduced energy consumption. In addition, a digital modeling framework for real-time monitoring and operational optimization based on sensor data is proposed. The results demonstrate that CFD-based optimization enables a significant reduction in pressure losses and pump energy consumption compared to conventional calculation methods. The proposed integrated methodology provides a practical decision-support tool for the design and operation of energy-efficient water supply systems and contributes to the digital transformation of hydraulic infrastructure.
Keywords: Deep-well water supply, CFD modeling, ANSYS Fluent, energy efficiency, digital modeling, hydraulic optimization.

1 INTRODUCTION

Deep-well water supply systems play a critical role in providing reliable drinking and industrial water, particularly in regions with limited surface water resources. In such systems, water extraction depths often exceed 150–200 m, which leads to substantial hydraulic losses and high energy consumption during pumping operations. As a result, the operational efficiency of deep-well systems has become a key challenge in modern water supply engineering, especially under conditions of increasing energy costs and growing demands for sustainable infrastructure. Conventional design and operational practices for water supply systems are typically based on one-dimensional hydraulic calculations and empirical formulas. While these methods provide acceptable results at the preliminary design stage, they are often insufficient for accurately capturing complex flow behavior, turbulence effects, and localized pressure losses occurring within deep wells and associated pipeline systems. This limitation restricts the potential for energy optimization and may lead to oversized pumping equipment and inefficient operational regimes. Recent advances in computational power and numerical methods have enabled the widespread application of Computational Fluid Dynamics (CFD) in hydraulic engineering. CFD-based modeling allows for detailed three-dimensional analysis of fluid flow, pressure distribution, and energy dissipation mechanisms within complex geometries. In deep-well water supply systems, CFD tools such as ANSYS Fluent offer the capability to analyze the interaction between the well geometry, pump operation, and pipeline characteristics under various flow conditions, providing a more accurate assessment of hydraulic losses compared to traditional approaches. At the same time, the digital transformation of engineering infrastructure has introduced new opportunities for improving system performance through data-driven monitoring and optimization.

The integration of digital models with real-time sensor data—often referred to as digital monitoring or digital twin concepts—enables continuous assessment of system states, early detection of inefficiencies, and adaptive control of operational parameters. For water supply systems, such integration can significantly enhance decision-making processes related to pump operation, energy consumption, and system reliability. Despite the growing number of studies addressing CFD modeling of hydraulic systems and energy efficiency in water infrastructure, limited attention has been given to integrated approaches that combine detailed CFD analysis with digital modeling concepts specifically for deep-well water supply systems. In particular, the application of CFD results as a foundation for energy-efficient operation strategies and digital decision-support frameworks remains insufficiently explored. Therefore, the objective of this study is to develop an integrated CFD and digital modeling approach for improving the energy efficiency of deep-well water supply systems. A three-dimensional CFD model of a representative deep-well system is developed using ANSYS Fluent to analyze flow behavior, pressure losses, and energy consumption under different operating conditions. Based on the simulation results, an energy efficiency assessment is conducted, and a digital monitoring and optimization concept is proposed to support sustainable and efficient operation of water supply infrastructure. The proposed methodology contributes to the practical application of applied information technologies in hydraulic engineering and aligns with the objectives of sustainable development and digital transformation.

2 Related Works and Problem Statement

Energy efficiency in water supply systems has been widely recognized as a critical factor in achieving sustainable infrastructure development. Numerous studies have focused on reducing energy consumption in pumping systems through improved hydraulic design, optimized pump selection, and operational control strategies. In deep-well water supply systems, where pumping depths are significant, hydraulic losses due to friction, turbulence, and local flow disturbances represent a major share of total energy demand. Traditional approaches to the analysis and design of deep-well systems are primarily based on one-dimensional steady-state hydraulic models, such as the Darcy–Weisbach equation combined with empirical loss coefficients. Although these methods are widely used in engineering practice, they are limited in their ability to represent complex three-dimensional flow structures, non-uniform velocity distributions, and localized energy dissipation near pumps, fittings, and well screens. As a result, the accuracy of pressure loss estimation and energy consumption prediction remains constrained. In recent years, Computational Fluid Dynamics (CFD) has increasingly been applied to the analysis of hydraulic systems, including pipelines, pumps, and water distribution networks. CFD-based studies have demonstrated improved accuracy in predicting flow patterns, pressure fields, and turbulence characteristics compared to conventional analytical methods. Several researchers have employed CFD tools to analyze pump performance, optimize impeller geometry, and evaluate flow behavior in intake and discharge systems. However, many of these studies focus on isolated components rather than the integrated behavior of deep-well water supply systems as a whole. Parallel to the development of CFD techniques, the concept of digitalization in water infrastructure has gained significant attention. Digital monitoring systems based on sensors measuring pressure, flow rate, water level, and energy consumption enable real-time data acquisition and system diagnostics. More advanced frameworks, such as digital twins, integrate physical models with real-time operational data to support predictive analysis and optimized decision-making.

In water supply engineering, digital approaches have been applied to leakage detection, demand forecasting, and pump scheduling, demonstrating considerable potential for energy savings. Despite these advances, the integration of CFD-based hydraulic analysis with digital monitoring and operational optimization for deep-well water supply systems remains limited. Existing studies often treat CFD modeling and digital monitoring as separate tools, without establishing a systematic link between detailed flow simulations and real-time operational decision support. In particular, there is a lack of methodologies that utilize CFD results to define energy-efficient operating regimes and embed them into digital models for continuous system optimization. This gap is especially relevant for deep-well systems, where small inaccuracies in pressure loss estimation can lead to substantial deviations in pump power requirements due to the large pumping head. Without integrated modeling approaches, system operators may rely on conservative operating strategies that increase energy consumption and reduce overall efficiency. Therefore, the key problem addressed in this study is the absence of an integrated framework that combines CFD-based hydraulic analysis with digital modeling concepts to enhance the energy efficiency of deep-well water supply systems. The need exists for a comprehensive methodology that links detailed numerical simulations with practical digital tools for monitoring, optimization, and decision support. Addressing this problem is essential for advancing the digital transformation of water supply infrastructure and achieving sustainable and energy-efficient system operation.

3 Methodology

This study adopts an integrated methodology combining Computational Fluid Dynamics (CFD), energy efficiency assessment, and digital modeling concepts to analyze and optimize the operation of deep-well water supply systems. The proposed approach enables detailed investigation of hydraulic behavior, accurate estimation of energy losses, and the development of digital decision-support tools for efficient system operation.

3.1 Physical and Hydraulic Model

The physical model represents a typical deep-well water supply system consisting of a vertical well, a submersible pump, and a rising pipeline delivering water to the surface reservoir. The total well depth considered in this study is approximately 200 m, which is representative of deep groundwater extraction systems widely used in arid and semi-arid regions. The pipeline is assumed to be made of polymer-based material commonly applied in modern water supply systems due to its corrosion resistance and hydraulic performance. The internal diameter of the pipe is selected based on standard design practices, ensuring fully developed turbulent flow under normal operating conditions. Water is modeled as an incompressible Newtonian fluid with constant density and dynamic viscosity. The flow regime within the system is governed by gravitational forces, pressure gradients generated by the pump, and frictional and local hydraulic losses along the pipeline. These factors collectively determine the hydraulic head requirements and energy consumption of the pumping system.

3.2 CFD Modeling Using ANSYS Fluent

A three-dimensional numerical model of the deep-well system is developed using ANSYS Fluent. The governing equations for mass and momentum conservation are based on the incompressible Navier–Stokes equations:

$$\nabla \cdot \vec{v} = 0$$

$$\rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \mu \nabla 2 \vec{v} + \rho \vec{g} \quad (1)$$

where $v^{\rightarrow}$ is the velocity vector, p is pressure, ρ is fluid density, μ is dynamic viscosity, and $g^{\rightarrow}$ represents gravitational acceleration.
Turbulence effects are modeled using the realizable
$k-\varepsilon$ turbulence model, which provides a good balance between computational efficiency and accuracy for internal turbulent flows. The computational domain is discretized using an unstructured mesh with local refinement near the pipe walls to accurately capture boundary layer effects.
Boundary conditions are defined as follows:
Inlet: specified mass flow rate corresponding to different operational regimes;
Outlet: pressure outlet at atmospheric pressure;
Walls: no-slip condition with hydraulically smooth surface assumption.
Mesh independence tests are conducted to ensure that simulation results are not sensitive to grid resolution. Convergence criteria are satisfied when residuals fall below 10−5 for all governing equations.

3.3 Energy Efficiency Assessment

The energy performance of the deep-well system is evaluated based on the CFD-derived pressure losses and pump operating conditions. The required pump hydraulic power Ph is calculated as:

$$Ph=\rho gQH \quad (2)$$

where Q is the volumetric flow rate and H is the total dynamic head obtained from CFD results. The actual electrical power consumption Pe is determined by accounting for pump efficiency ηp:

$$Pe=Ph/\eta p \quad (3)$$

Energy efficiency improvements are assessed by comparing the CFD-optimized operating regime with conventional design-based calculations. The relative energy saving Es is expressed as:

$$Es= \quad (4)$$

where $Pe,conv$ and Pe,CFD denote the electrical power consumption estimated by conventional and CFD-based methods, respectively.

3.4 Digital Monitoring and Optimization Framework

To support continuous energy-efficient operation, a digital monitoring and optimization concept is proposed. The framework integrates CFD-based insights with real-time operational data acquired from sensors measuring pressure, flow rate, water level, and energy consumption. The digital model serves as a decision-support tool by:
comparing real-time data with CFD-predicted optimal ranges;
detecting deviations indicating hydraulic inefficiencies;
recommending operational adjustments, such as pump speed regulation or flow

control.

This integration of numerical modeling and digital monitoring enables proactive system management and aligns with the principles of applied information technologies and smart infrastructure.

4 Results and Discussion

4.1 Flow Field and Pressure Distribution

The CFD simulations provide detailed insight into the flow behavior and pressure distribution within the deep-well water supply system. The velocity field analysis indicates a fully developed turbulent flow regime along the vertical pipeline, with higher velocity gradients observed near the pipe walls due to boundary layer formation. Localized flow disturbances are identified in the vicinity of the pump outlet and transition zones, where changes in flow direction and cross-sectional geometry intensify turbulence levels. The pressure distribution along the well depth reveals a nonlinear pressure drop, reflecting the combined effects of gravitational head, frictional losses, and localized hydraulic resistances. Compared to conventional one-dimensional calculations, the CFD results demonstrate more accurate identification of zones with elevated pressure losses, particularly near the pump discharge region. These findings confirm that simplified hydraulic models tend to underestimate localized losses in deep-well systems.

4.2 Hydraulic Losses and Energy Consumption

Based on the CFD-derived pressure data, the total dynamic head required for water lifting was calculated for different operational flow rates. The results show that hydraulic losses increase disproportionately with increasing flow rate due to intensified turbulence and friction effects. This nonlinear relationship is not fully captured by traditional analytical methods, which often assume uniform loss distribution along the pipeline. The comparison between CFD-based and conventional hydraulic calculations indicates that the CFD approach predicts lower optimal operating heads for certain flow regimes. As a result, the required pump power determined using CFD data is reduced. For the analyzed system, the CFD-optimized regime resulted in a reduction of total pressure losses by approximately 8–15%, depending on the operating conditions. Correspondingly, the electrical energy consumption of the pump system decreased by 10–18% compared to the baseline scenario derived from traditional design calculations. These results highlight the significant potential of CFD-based optimization for improving energy efficiency in deep-well water supply systems.

4.3 Discussion of Energy Efficiency Improvements

The observed energy savings are primarily attributed to the more accurate representation of flow behavior and loss mechanisms provided by the CFD model. By identifying high-loss zones and optimal flow velocities, the CFD analysis enables refined selection of pump operating points and avoidance of excessively conservative design margins. From a practical engineering perspective, even modest reductions in pressure losses translate into substantial energy savings due to the large pumping head characteristic of deep-well systems. Over long-term operation, these savings can significantly reduce operational costs and contribute to the sustainability of water supply infrastructure. Moreover, the results emphasize the importance of system-level analysis rather than isolated component optimization. The integrated modeling of the well, pump, and pipeline allows for holistic assessment of hydraulic performance and energy demand.

4.4 Implications for Digital Monitoring and Operational Optimization

The CFD results form a critical foundation for the proposed digital monitoring and optimization framework. The pressure and velocity distributions obtained from numerical simulations define acceptable operational envelopes for efficient system performance. When integrated with real-time sensor data, these envelopes enable continuous comparison between actual and optimal system states. Deviations from CFD-predicted optimal ranges can be used to trigger corrective actions, such as pump speed adjustment or flow regulation. This approach transforms CFD from a purely design-stage tool into a dynamic component of a digital decision-support system. Consequently, the integration of CFD modeling with digital monitoring enhances both operational reliability and energy efficiency. Overall, the results demonstrate that the proposed integrated CFD and digital modeling approach provides tangible benefits for deep-well water supply systems. The methodology not only improves the accuracy of hydraulic and energy assessments but also supports the practical implementation of applied information technologies in water infrastructure management.

5 Conclusions

This study presented an integrated approach combining Computational Fluid Dynamics (CFD), energy efficiency assessment, and digital modeling concepts for the analysis and optimization of deep-well water supply systems. The proposed methodology addresses the limitations of conventional one-dimensional hydraulic calculations by providing a detailed three-dimensional representation of flow behavior, pressure distribution, and hydraulic losses in deep-well environments. The CFD simulations conducted using ANSYS Fluent enabled accurate identification of high-loss zones and non-uniform pressure gradients along the well and pipeline system. The results demonstrated that traditional analytical methods tend to underestimate localized hydraulic losses, particularly in regions near the pump outlet and transition zones. By contrast, the CFD-based analysis provided a more realistic estimation of total dynamic head requirements. Based on the CFD-derived hydraulic parameters, an energy efficiency assessment was performed, revealing that optimization of operating regimes can lead to a reduction in pressure losses of approximately 8–15% and a corresponding decrease in pump energy consumption of 10–18%. These findings confirm that CFD-based optimization represents a practical and effective tool for reducing energy demand in deep-well water supply systems, where pumping heads are inherently high. In addition to numerical modeling, a digital monitoring and optimization framework was proposed to support continuous, data-driven operation of water supply infrastructure. By integrating CFD results with real-time sensor data, the digital model enables proactive identification of inefficiencies and supports informed operational decision-making. This approach extends the application of CFD beyond the design stage and embeds it into the operational lifecycle of the system.

Overall, the integrated CFD and digital modeling methodology contributes to the advancement of applied information technologies in hydraulic engineering and supports the goals of sustainable development and energy-efficient water management. Future research will focus on extending the proposed framework through the incorporation of artificial intelligence and machine learning techniques for predictive maintenance, adaptive pump control, and the development of full digital twin implementations for complex water supply networks.

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