Journal of Applied Fluid Mechanics, Vol. 18, No. 9, pp. 2202-2211, 2025.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
https://doi.org/10.47176/jafm.18.9.3428

Back-turn Approach for Optimal Operation of Booster Pump Systems

Y. S. Bae[1], M. D. Islam[2,3], D. Y. Choi[1], H. J. Kang[4], S. J. Tae[4], and H. H. Kim[4†]

[1] *Sego Industry Pump, Bongsu-daero, Seo-Gu, Incheon, Gyeonggi-do, 22845, South Korea*
[2] *Department of Mechanical Engineering, Graduate School of Engineering, Gyeongsang National University, Jinju, Gyeongnam, 52725, South Korea*
[3] *Department of Mechanical Engineering, International University of Business Agriculture and Technology, Uttara, Dhaka, 1230, Bangladesh*
[4] *School of Aerospace Engineering, Gyeongsang National University, Jinju, Gyeongnam, 52725, South Korea*

†*Corresponding Author Email: khh106@gnu.ac.kr*

ABSTRACT

Conventional pumping techniques frequently fail to optimize energy use in commercial and residential high-rise buildings. This study examines creative scheduling and operational techniques with an emphasis on back-turn operations that improve operational efficiency and save energy in booster pump systems. In addition, the study demonstrates significant energy use savings while preserving system efficiency by examining water consumption trends in high-rise residential and commercial buildings. Over 24 h of back-turn operations key findings showed power usage reductions of up to 5.05% in residential units and 5.84% in commercial buildings. With the use of sophisticated control systems and real-time data monitoring, the back-turn operating approach dynamically modifies pump sequences to optimize efficiency. In addition to saving energy, this method prolongs the pump's life by avoiding ineffective high-flow operations. The findings highlight the significance of strategic pump management as an economical and sustainable solution for urban water delivery systems, particularly in rapidly developing areas. Altogether, this study emphasizes the necessity of flexible management strategies to address energy inefficiencies, supporting the long-term expansion of urban infrastructure.

Article History

Received February 6, 2025
Revised April 17, 2025
Accepted May 1, 2025
Available online July 5, 2025

Keywords:

Booster pumps
Pump scheduling
Energy efficiency
Operational optimization
Energy savings

1. INTRODUCTION

Optimization is widely used in pump research and is essential for improving the efficiency of mechanical systems (Koor et al., 2016; Fadaei Rodi et al., 2024; Rakibuzzaman et al., 2024). In the context of energy-efficient and sustainable engineering, using booster pump systems to optimize power and improve efficiency offers a substantial opportunity to improve water supply. Booster pumps are increasingly used in high-rise buildings to guarantee that water is delivered at the necessary pressures, allowing pump companies to ensure a steady supply to all customers

(Pedersen & Yang, 2008; Weber & Lorenz, 2017). Optimizing power consumption in managing water distribution using booster pumps in multistory buildings, office complexes, and public institutions presents a problem because conventional operating techniques frequently fail to achieve the best possible energy use in commercial and residential high-rise buildings (Diaz et al., 2017; Groß et al., 2017; Hossain et al., 2023). Therefore, rearranging the booster pump sequence to increase efficiency is a substantial advancement in water delivery technology for contemporary high-rise structures (Zhang et al., 2012; Nogueira Vilanova & Perrella Balestieri, 2014; Nikolenko & Ryzhakov, 2020). System performance can be significantly enhanced and energy consumption can be reduced by implementing efficient scheduling and optimization techniques. These tactics include evaluating the state of each pump to improve efficiency and progressively lower energy usage (Arun Shankar et al., 2016; Makaremi et al., 2017). Consistent performance is ensured by optimally operating booster pump systems, which integrate cutting-edge flow measuring and control technology to reduce energy usage (Derakhshan & Nourbakhsh, 2008; Yang & Borsting, 2010; Müller et al., 2019). Implementing an optimal booster pump installation technique and conducting accurate assessments of pump flow and efficiency will result in an optimal pumping configuration.

Typically, booster pump systems use several multistage centrifugal pumps that operate together (Ye et al., 2022). Conventional operating techniques frequently waste significant energy by prioritizing the maximum flow above peak efficiency (Khramshin et al., 2014). This study presents a technique to improve the efficiency of current booster pump systems that typically use multistage centrifugal pumps running in parallel to address this problem. These systems generally have three identical pumps operating simultaneously. The first pump works at its maximum flow rate above its ideal operating point and the second and third pumps are activated if the required flow rate increases further. When the second pump is turned on, the first pump lowers its output to its ideal level. When the three pumps are connected in parallel, the first two return to their ideal levels rather than running at an inefficient maximum flow.

The proposed "back turn" method optimizes the parallel operation of the ongoing operation systems. The first pump reduces its output to its optimal operating point upon activation of the second pump; when the three pumps operate in parallel, the first two revert to their optimal functioning instead of operating at an inefficient maximum flow. Energy conservation and increased operational lifespan can be promoted by reducing excessive stress and the possibility of damage linked to continuous maximum flow operation (Furman, 2020).

Additionally, this study utilizes the energy-saving rate linked to flow patterns reported previously (Fernández García et al., 2017; da Silveira & Mata-Lima, 2021). Furthermore, experimental evaluations based on the flow demands of commercial properties and high-rise buildings have been used to design and validate the performance analysis of the recently introduced booster pump system with a new algorithm for the collective operation of booster pump systems. The results validate the energy-saving impacts and show that using sophisticated control strategies and tactical operational adjustments significantly improves energy efficiency. Adapting to changing demand patterns allows the booster pump system to operate more efficiently, resulting in significant long-term energy and cost savings.

2. Booster Pump Operation Scheduling

2.1 Booster Pump Configuration for Operation

To effectively manage the pump performance and system stability, a booster pump system usually functions as a packaged unit comprising numerous vertical multistage pumps, sensors, and a centralized control panel (Rakibuzzaman et al., 2022). A network of sensors that measure important factors, including pressure, temperature, and flow rate, checks every pump in real-time. A control panel is used to display and manage these data, allowing operators to monitor pump performance and make necessary adjustments.

The rotational activation sequence is a common operating method for a three-pump booster system. As shown in Fig. 1, this cycle—pump 1 → pump 2 → pump 3—repeats over a predetermined time, guaranteeing that each pump is used proportionately.

Fig. 1 Booster pump system

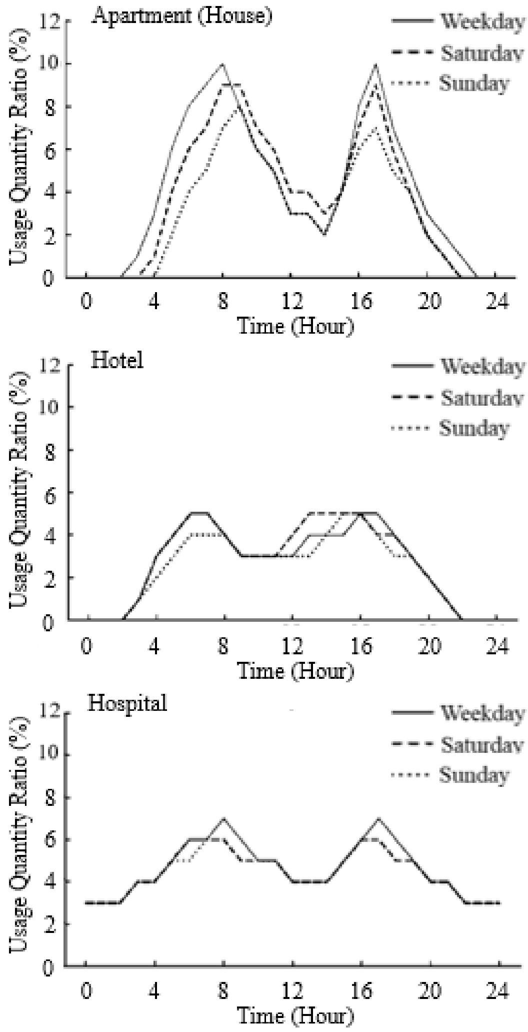

Fig. 2 Water supply load in major infrastructures

As shown in Fig. 2, the water supply load pattern of the building uses various water supply patterns to perform variable speed control, regardless of the load and pattern, which may lead to a shortening of the pump life and an imbalance in water supply quality (Heo et al., 2016). The booster pump system regulates its discharge rate following the maximum flow of each pump capacity and maintains

Fig. 3 Pump station used in water supply infrastructure

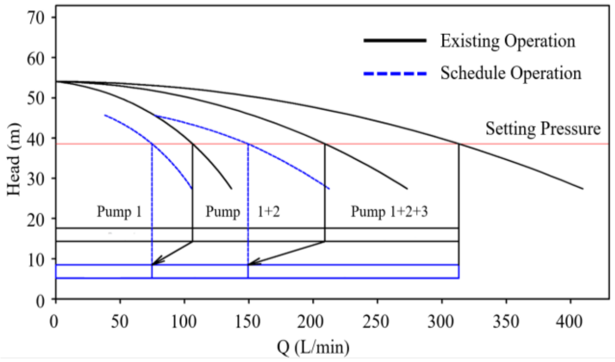

Fig. 4 Back-turn strategy for optimal operation

a steady pressure at the endpoint of the pipeline to efficiently handle these variations.

When the demand changes, the system compensates for the differences in the total flow rate by either adjusting the rotational speed of the pumps or adding lower-capacity pumps. The system can match the flow rate to the current demand by varying pump speed, thereby saving energy during low-demand periods and preventing strain during peak usage. When more precise adjustments are required, additional lower-capacity pumps can be activated to handle minor variations without running the entire system, thus enhancing efficiency and prolonging equipment lifespan.

2.2 Scheduling Operation

By using pumps under optimal conditions and continuously monitoring them to favor the most efficient units, scheduling activities in collective pump systems can maximize efficiency. Based on the performance data collected in real-time, this scheduling strategy can result in energy savings while using rotational pumps (Luna et al., 2019). A system with three subsequent pump turns enables each pump to run within its ideal range and lowers the total energy usage (Nguyen et al., 2024). Large pumping stations have been operating frequently on a scheduled basis since the early 2000s (Pinto et al., 2000). These techniques enable the best scheduling choices by measuring efficiency through changes in fluid temperature and pressure (Coelho & Andrade-Campos, 2014).

Booster pump systems often have limited five-dimensional clearance around pipes in confined spaces, as shown in Fig. 3, making the installation of flow meters required for accurate readings challenging. Additionally, this constraint hinders precise flow rate monitoring and effective pump efficiency evaluations. Therefore, systems with limited space flow sensors and sophisticated control algorithms provide alternative scheduling methods that enable efficient operation even under installation constraints.

2.3 Optimal Operation Method

In scenarios where multiple pumps of the same model operate collectively, these pumps should ideally function with uniform efficiency; however, the efficiency of booster pump systems varies between pumps (Østergaard & Andersen, 2016) . This variation arises from differences in operating conditions within the confined spaces of the piping assembly of the booster pump system, where piping losses during pump operations can affect performance. Therefore, even when three identical pumps are selected randomly and operated together, their performances are not identical because the piping losses resulting from different lengths and configurations of the pipe segments linked to each pump cause performance variations. Furthermore, booster pump systems are typically operated to achieve maximum flow rates rather than at their optimal or most efficient points. Consequently, the operating points for maximum flow rate and optimal efficiency are distinct.

In general, existing booster pump systems prioritize achieving maximum flow rates over maximizing efficiency. This is comparable to assessing the state of racehorses at the beginning of a race; just as evaluating and selecting the horses according to their preparedness is necessary, comprehending the locations and states of the pumps in a booster system is also critical to prioritize those producing the best results.

Instead of letting the first pump run inefficiently at the maximum flow, as shown in Fig. 4, the back-turn operational strategy returns it to its optimal operating point once the second pump starts up. The efficacy and energy-saving benefits of the method were confirmed through experimental testing and evaluation.

As shown in Fig. 5, the back-turn action ensures that when three pumps function parallelly, the first pump resumes its ideal performance rather than running inefficiently at the maximum flow. Similarly, when the second pump reaches its maximum flow capacity, the third pump is activated to restore optimal operation.

This operational modification improves the booster pump system's overall performance and drastically lowers energy usage by maintaining the efficiency of each pump.

2.4 Computational Methodology

The three-dimensional pump model (SM 510), a multi-stage (vertical) inverter-driven in-line centrifugal pump for booster pump systems, is depicted in Fig. 6. The complete computer-aided design model of the pump is divided into stationary (casing) and rotating (impeller) components.

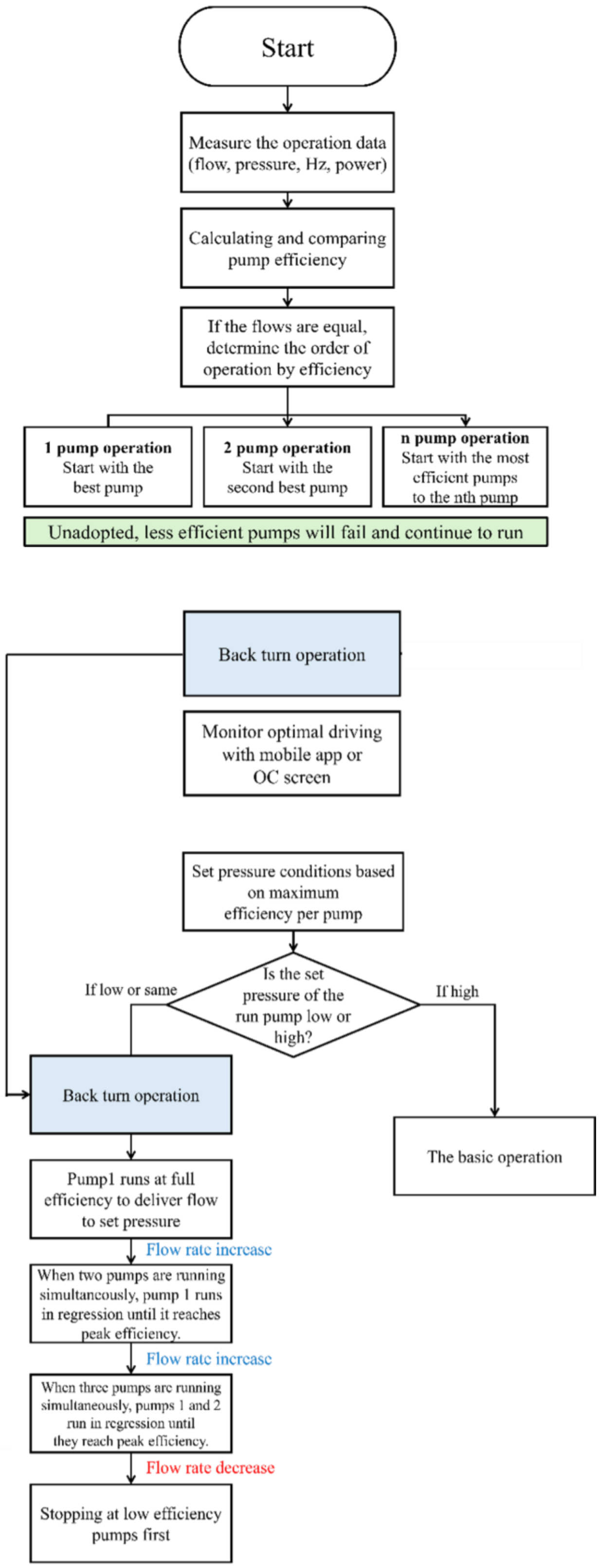

Fig. 5 Back-turn operating flowchart for a booster pump system

Subsequently, the booster pump system, including suction and discharge pipes, is modeled with unstructured prism–tetrahedral grids and mesh, as shown in Fig. 7. The total number of grid elements and nodes are 21,139,942 and 5,236,763, respectively.

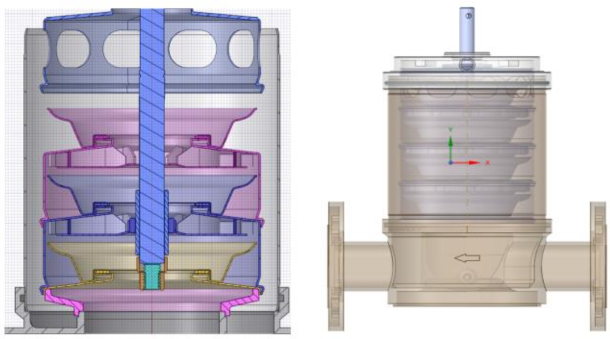

Fig. 6 Illustration of the 3-kW in-line centrifugal pump model

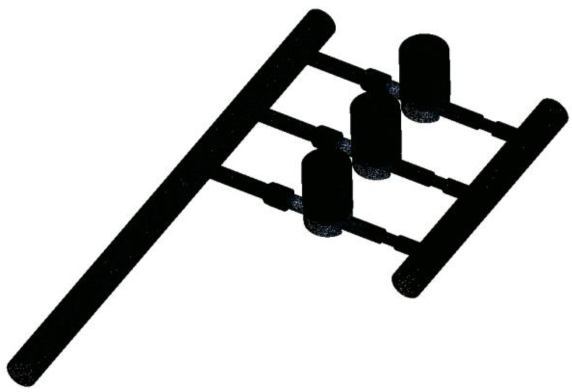

Fig. 7 Meshing grids for the booster pump system

The flow characteristics inside the pump were investigated using ANSYS CFX 20 R1 (Ansys Inc., 2013). The continuity and momentum equations served as the governing equations for numerical analyses.

The CFX solver used was a pressure-based algebraic-multigrid-coupled solver. The advection terms were discretized using a hybrid differencing scheme to enhance stability. Challenges in determining the convection coefficients from the node-centered velocities required on the node faces were addressed by implementing a Rhie–Chow interpolation scheme within the code. This scheme facilitated the effective management of mass–source residuals and velocity–pressure coupling.

Figure 8 shows the full computational domain used for numerical simulations. In this domain, the impeller domain was designated as rotating, with its y-axis at a rotational speed of 3500 rpm, whereas the casing domain remained stationary.

The total pressure was employed as the entrance boundary condition for cavitation, and the mass flow rate was selected as the outflow boundary condition. All the boundary walls in the near-wall zone were treated as smooth, non-slip surfaces, and an automatic wall function was applied.

The turbulence viscosity was calculated using the shear–stress transport turbulence model (Georgiadis et al., 2006; Ansys Inc., 2013). The convergence residual value was set to 1×10^{-5} to ensure numerical convergence.

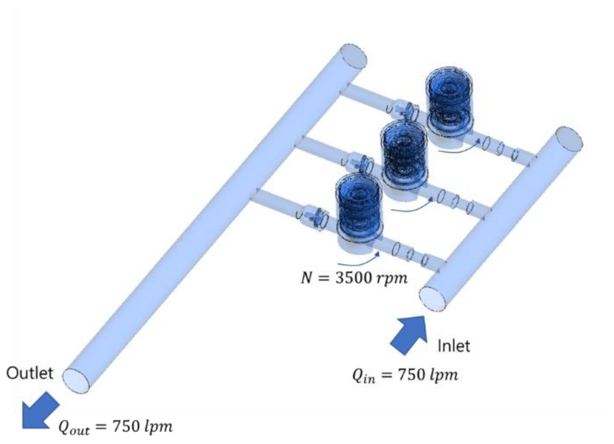

Fig. 8 Computational domain of the booster pump system

Table 1. Specification of booster pump system for experimental setup

Parameters	Booster pump system data
Number of pumps	3
Pipe diameter (mm)	32
Flow rate (L/min)	110
Head (m)	80
Power (kW)	3
Rotational speed (rpm)	3490
Motor specifications	380 V/ 60 Hz/ 5.96 A/ 2 P

3. Experimental Methods

3.1 Experimental Setup

The experimental setup in this study was created to assess both the performance of the individual pump and the overall operation of the booster pump system, as presented in Table 1 and Fig. 9. Both the suction and discharge pipes have pressure gauges placed at their midpoints, as shown in Fig. 9(a). An electronic flow meter was attached at the discharge end to record the flow rate. The average deviation and uncertainties of the measuring devices were tracked during pump testing and were found to be 0.11±0.02% and 0.25%, respectively. The experiments were conducted using the working fluid at 20.8 °C, a temperature of 29.3 °C, and 79% relative humidity.

3.2 Section and Subsection Headings

The initial assessment evaluated the performance of three identical pumps—P1, P2, and P3—arranged in sequence based on proximity to the pressure tank, with P1 closest, followed by P2 and P3. Flow rate-head and flow rate-efficiency characteristics were measured for each pump, as shown in Fig. 10.

According to the data P1, P2, and P3 all demonstrated the same performance traits under the same installation and operating circumstances with no discernible differences. This uniformity makes it possible to rely on

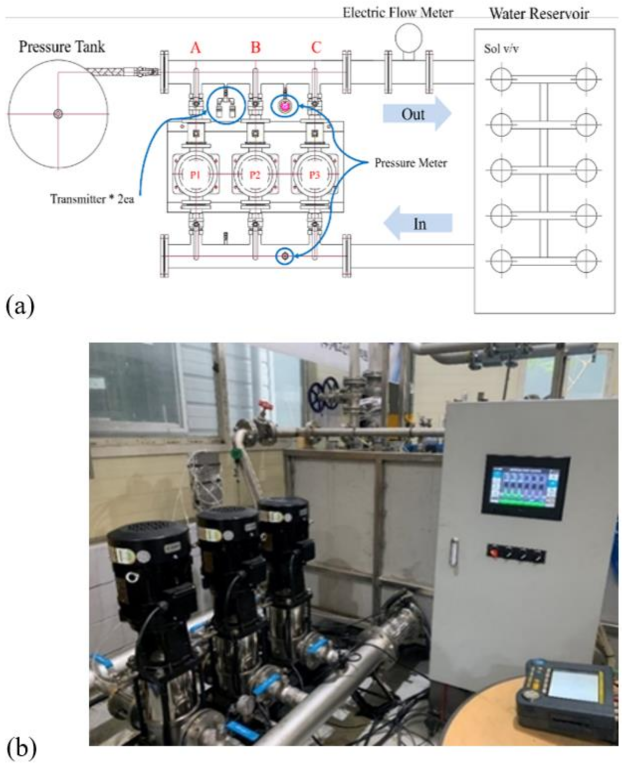

Fig. 9 Experimental setup of the pump system: (a) Schematic of the setup (b) Fabricated experimental setup

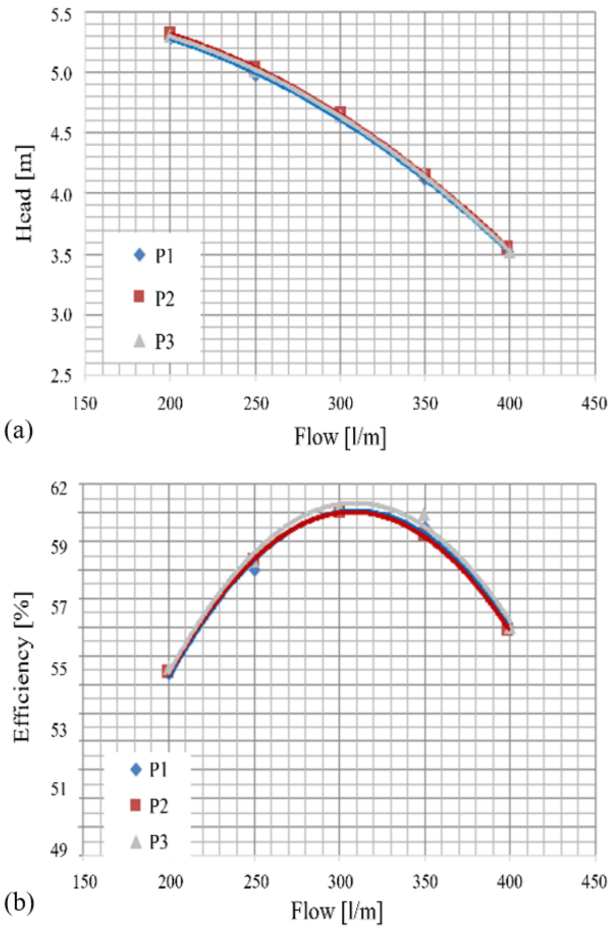

Fig. 10 Performance curves of three booster pumps selected at random: (a) Head-flow curve (b) Efficiency-flow curve

Table 2 Experimental results for different patterns of pumps

Driving pattern	Flow rate (LPM)	Pressure (bar)	Power (kW)	Current (A)
P1→P2→P3	750.2	5.006	11.58	23.30
P1→P3→P2	749.5	4.999	11.60	23.07
P2→P1→P3	748.8	5.008	11.57	23.37
P2→P3→P1	749.1	5.016	11.57	22.51
P3→P1→P2	748.3	5.035	11.63	22.90
P3→P2→P1	749.1	5.038	11.60	23.32

(a) P1→P2→P3 (b) P1→P3→P2

(c) P2→P1→P3 (d) P2→P3→P1

(e) P3→P1→P2 (f) P3→P2→P1

Fig. 11 Operational modes of the three pumps

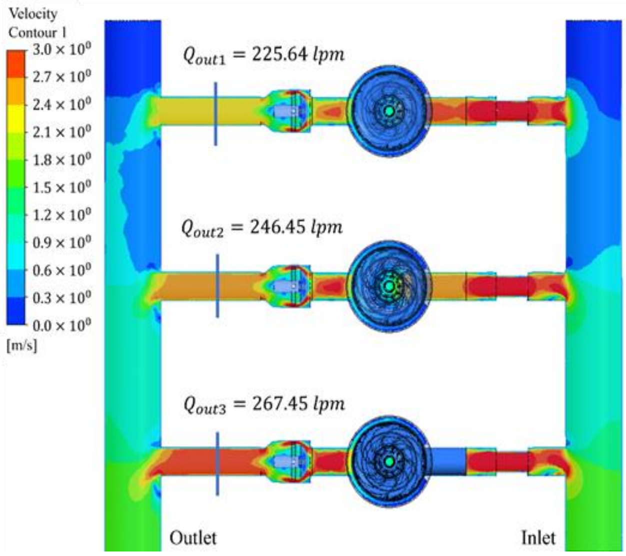

Fig. 12 Pressure distribution of booster pump system

each pump to function similarly, which streamlines operational choices and improves system reliability by enabling balanced load distribution across all pumps.

4. RESULTS AND DISCUSSION

4.1 Performance Analysis of the Pump According to Installation Position

To examine the impact of the installation positions on the performance of three identical pumps, each pump is systematically moved in various configurations, as depicted in Fig. 11, after being originally assessed in the configuration depicted in Fig. 9(b). The pumps in Fig. 11(a) run in order, starting with pump 1, followed by pumps 2 and 3. An alternate configuration is depicted in Fig. 11(b), where the locations of pumps 2 and 3 are reversed, resulting in a sequence in which pump 1 runs first, followed by pump 3 and finally pump 2. Additional configurations are shown in Fig. 11(c)–11(f), each of which introduces a new order of operation to investigate the entire spectrum of positional effects on pump performance.

Experiments were conducted to evaluate the performance under six different scenarios based on the position of the three pumps. The operational performance of the pumps was measured by setting the discharge pressure of each pump to 5 bars and monitoring the maximum flow discharge. The results, presented in Table 2, reveal flow rates ranging from 748.3 to 750.2 LPM, pressures from 4.999 to 5.038 bar, and power consumption from 11.57 to 11.63 kW. These variations indicate that even identical pumps can perform differently based on their installation positions and operational patterns.

As listed in Table 2, the outcome of every pump configuration exhibits notable differences in the power consumption and flow rates, underscoring the impact of the pump sequence on the operational dynamics and system efficiency. These results highlight the need to optimize pump scheduling to improve the overall system performance.

The discharge flow rate results from Table 1 reveal different flow rates depending on the pump operation sequence. Ideally, the same pump should discharge the same flow rate in all the scenarios. To investigate this numerically, computational fluid dynamics analysis is conducted as detailed in Fig. 12, and the flow rate on the discharge side is varied for each configuration, totaling 750 LPM, as shown in the computational methodology. This variation is attributed to the resistance and loss in the confluence pipe of the discharge system. These results indicate that the conventional method of assuming uniform pump flow rates for efficiency calculations is flawed. Instead, the pressure and flow rate should be calculated separately, considering piping losses, which is a critical consideration during the optimization stage of pump operation. Current practices in the field often overlook this with confluence pipes typically not designed optimally, which require further study.

Table 3 Experimental results for energy savings

Operating pattern type	Total power (power-number)	Power consumption		Energy savings	Energy saving rates
		Current method	Optimal method		
High-rise apartment pattern	12 kW (4 kW-3)	99.21 kWh	96.22 kWh	2.99 kWh	3.01%
Commercial and building patterns	12 kW (4 kW-3)	108.34 kWh	103.88 kWh	4.46 kWh	4.11%
High-rise apartment pattern	22.5 kW (7.5 kW-3)	148.89 kWh	142.88 kWh	6.01 kWh	4.04%
Commercial and building patterns	22.5 kW (7.5 kW- 3)	162.51 kWh	153.82 kWh	8.68 kWh	5.34%
High-rise apartment pattern	33 kW (11 kW-3)	176.887 kWh	167.96 kWh	8.93 kWh	5.05%
Commercial and building patterns	33 kW (11 kW-3)	235.46 kWh	220.17 kWh	15.29 kWh	6.50%

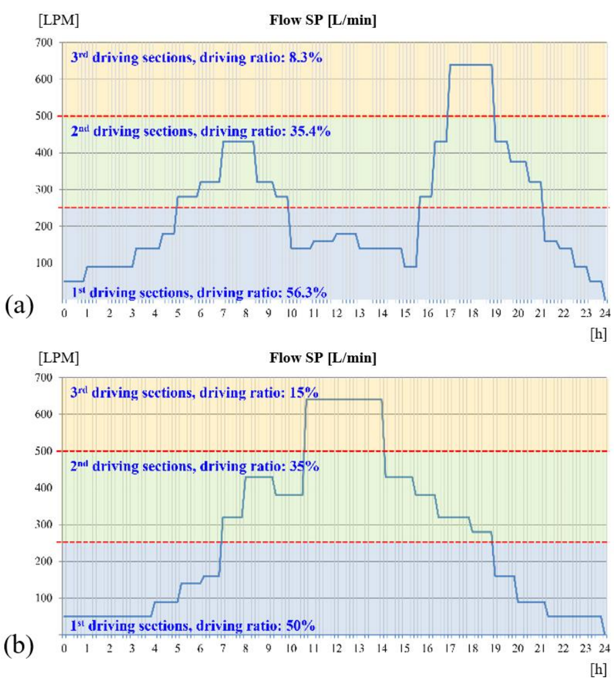

Fig. 13 Applied flow patterns for the experiment: Daily flow pattern of (a) high-rise apartments and (b) commercial buildings

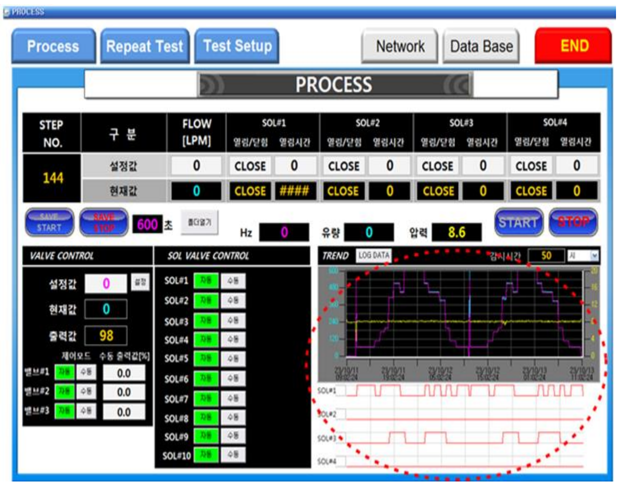

Fig. 14 Utilization of solenoid valves to match flow patterns

4.2 Optimal Operation through Back-Turn in Booster Pump Systems

An ideal operation technique, such as the back-turn operation shown in Fig. 9, has been suggested considering the variance in pump characteristics depending on their location within the booster pump system. As shown in Fig. 10, this technique is used to model daily flow patterns in commercial and high-rise apartment buildings. The discharge pressure in this experiment was set to 3.5 bar and three pumps were used.

According to Fig. 13(a), the operating ratios for high-rise apartments are 56% for single pumps, 35% for dual pumps, and 8% for triple pumps. The operation ratios are 50% for single pumps, 35% for dual pumps, and 15% for triple pumps in commercial buildings, as illustrated in Fig. 13(b). According to this comparison, triple pump operation is more common in business buildings (15%) than in high-rise residences (8%), suggesting that triple parallel operation is more common in commercial settings.

To implement the proposed method, 10 solenoid valves (referred to as sol valves) are installed at the end of the discharge pipe in the experimental setup shown in Fig. 6(a), to match the flow patterns depicted in Fig. 11. The status of the opening and closing of the sol valves is shown in the lower right corner of Fig. 14, accurately reflecting the operational patterns.

Considering the variance in pump efficiency based on positional factors, we evaluated the shaft power values rather than the flow rate values of each pump. The results of this evaluation, presented in Table 3, reveal that an increase in the pump elevates the energy savings achieved through the back-turn method.

4.3 Energy Savings

The pump performance in booster pump systems operating at variable speeds cannot be assessed solely through efficiency owing to the variable nature of operating speeds. Instead, a method of evaluating performance based on energy usage has been employed (Derakhshan & Nourbakhsh, 2008). Figure 15 compares the power consumption when applying flow patterns typical of apartments and commercial buildings.

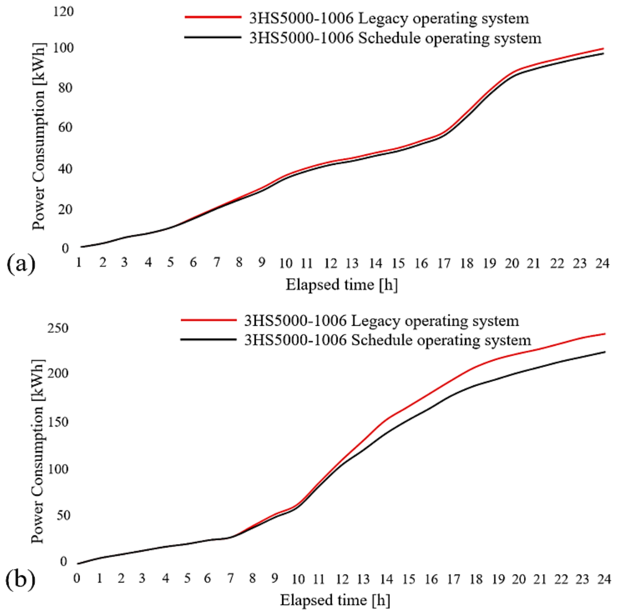

Fig. 15 Comparative power consumption: (a) Apartment (b) Commercial building

The results reveal that using the same flow patterns, the applied product demonstrates a power consumption of 3.039 kW for both apartment and commercial patterns, resulting in savings of approximately 14.865 kWh. This translates to energy savings of approximately 3.01% for 4 kW pumps (three units, totaling 12 kW) and 6.50% for 11 kW pumps (three units, totaling 33 kW).

The greater energy savings observed in the commercial pattern are attributed to the more extensive and frequent combined operations required by larger commercial settings. It is posited that utilizing large-capacity pumps more frequently or enhancing combined operations could further increase energy savings.

The reduction in power consumption, as shown in Fig. 15, is primarily due to the back-turn operation, which involves reverting to and maintaining the optimal operation point presented in Fig. 4, rather than operating at the maximum flow, which is often less efficient. Effective control of power increases during the maximum operation, as shown in Fig. 16, and is considered to contribute to these savings.

4.4 Overall Discussion

The potential significance of energy savings and increased operational efficiency in booster pump systems was analyzed by back-turn operation through innovative scheduling and operational strategies. Commonly used booster pumps were analyzed to identify efficiency gains in high-rise buildings and commercial apartment complexes (Midiani et al., 2023). The system equipped with three identical pumps exhibits discrepancies in power values, as noted in Table 2, owing to variations in flow resistance within the pipes, which affects the shaft power based on the pump placement. The order P3→P2→P1 proves that the most efficient sequence of identical pumps performs differently as highlighted by our finding, thus underscoring the importance of strategic pump scheduling

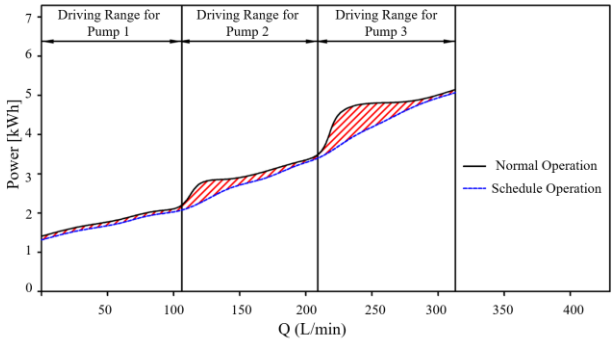

Fig. 16 Power control and maximizing operation

to reduce energy inefficiencies and operational costs. Beginning operations with the most efficient pump enhances overall system efficiency as the conventional setup fails to achieve optimal performance (Barán et al., 2005; Li et al., 2024).

The conventional and back-turn operation methods are compared for water consumption patterns for high-rise apartments and commercial buildings, as shown in Fig. 13. The analysis reveals significant energy savings, as highlighted in Table 3. Power consumption over 24 h decreased by 3.76%, 4.04%, and 5.05% in apartment patterns, and power savings over the same period were 4.11%, 5.34%, and 5.84% in commercial and office building patterns. These outcomes indicate that energy savings increase in proportion to power consumption. The data from Fig. 15 show that commercial and office building patterns are more effective in reducing power consumption than apartment patterns with a higher proportion of triple pump collective operations in commercial settings (15%) (Fig. 13) compared to apartments (8%).

A more thorough examination demonstrates that the back-turn method reduces power consumption by returning to the system's ideal operating position, as shown in Fig. 5. As shown in Fig. 16, this method prevents inefficient maximum flow conditions while preserving optimal functioning and managing power increases that usually follow maximum flow scenarios. To run each pump at its peak efficiency, the system tracks the performance of each pump and constantly modifies the operational sequence. In high-rise apartment complexes, a single pump operates at maximum efficiency until the demand increases. At that moment, the second pump operates and the first pump modifies its flow to continue operating efficiently. The benefits of this back-turn operation include avoiding ineffective maximum flow activities, significantly lowering energy consumption and increasing pump longevity by reducing the strain from constant maximum flow operations. This indicates that the life of booster pump systems increases with the back-turn approach while also saving electricity. Thus, the experimental findings of the back-turn method emphasize sustainability and efficiency, thereby providing major energy consumption demand trends in residential and commercial buildings.

5. CONCLUSION

The back-turn approaches in this study enhance the operational durability and energy efficiency of the booster pump system. Significant energy conservation over a 24-h duration and the operational efficiency of booster pumps are the key findings of this research.

Energy use was reduced by 3.76%, 4.04%, and 5.05% in high-rise apartment buildings and by 4.11%, 5.34%, and 5.84% in commercial and office buildings per the experimental output. These indicate that energy savings and power consumption are positively correlated with the frequent collective operation of pumps in the back-turn approach.

However, this investigation was conducted with a restricted range of pump designs in a controlled experimental setting. Other elements, such as aging equipment, long-term damage, and variations in water quality, may affect system performance in real-world applications. Furthermore, the difficulties of installation and system integration in pump stations with limited spaces should be considered in future implementations.

Multi-objective optimization techniques that consider the lifespan cost, system stability, operational redundancy, and energy savings will be investigated in future research to address these problems. Additionally, the efficiency, responsiveness, and dependability of booster pump systems in intricate urban settings can be significantly increased by integrating advanced control systems with artificial intelligence and Internet of Things technologies. These systems include real-time adaptive scheduling, load forecasting, and predictive maintenance.

Therefore, the back-turn operational strategy is a sustainable approach to manage water supply in modern architectural constructions such as high-rise apartment buildings and commercial and office buildings.

ACKNOWLEDGEMENTS

This study was supported by the Glocal University 30 Project Fund of Gyeongsang National University in 2025.

CONFLICT OF INTEREST

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

AUTHORS CONTRIBUTION

Young-Suk Bae: Data curation, formal analysis, investigation, methodology, resources. **Md. Didarul Islam:** Data curation, formal analysis, investigation, methodology, software, writing–original draft, writing – review and editing. **Du-Yeol Choi:** Data curation, formal analysis, investigation, resources, and software. **Hyo Jeong Kang:** Data curation, formal analysis, and software. **Sung Jin Tae:** Data curation, formal analysis, and software. **Hyoung-Ho Kim:** Conceptualization, funding acquisition, investigation, methodology, supervision, writing–original draft, writing – review and editing.

REFERENCES

Ansys Inc. (2013). ANSYS-CFX (CFX Introduction, CFX Reference Guide, CFX Tutorials, CFX-Pre User's Guide, CFXSolver Manager User's Guide, Theory Guide), release 14.5, USA.

Arun Shankar, V. K., Umashankar, S., Paramasivam, S., & Hanigovszki, N. (2016). A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system. *Applied Energy*, *181*, 495–513. https://doi.org/10.1016/j.apenergy.2016.08.070

Barán, B., von Lücken, C., & Sotelo, A. (2005). Multi-objective pump scheduling optimisation using evolutionary strategies. *Advances in Engineering Software*, *36*(1), 39–47. https://doi.org/10.1016/j.advengsoft.2004.03.012

Coelho, B., & Andrade-Campos, A. (2014). Efficiency achievement in water supply systems—A review. *Renewable and Sustainable Energy Reviews*, *30*, 59–84. https://doi.org/10.1016/j.rser.2013.09.010

da Silveira, A. P. P., & Mata-Lima, H. (2021). Assessing energy efficiency in water utilities using long-term data analysis. *Water Resources Management*, *35*(9), 2763–2779. https://doi.org/10.1007/s11269-021-02866-8

Derakhshan, S., & Nourbakhsh, A. (2008). Theoretical, numerical and experimental investigation of centrifugal pumps in reverse operation. *Experimental Thermal and Fluid Science*, *32*(8), 1620–1627. https://doi.org/10.1016/j.expthermflusci.2008.05.004

Diaz, C., Ruiz, F., & Patino, D. (2017). Modeling and control of water booster pressure systems as flexible loads for demand response. *Applied Energy*, *204*, 106–116. https://doi.org/10.1016/j.apenergy.2017.06.094

Fadaei Rodi, R., Kamali, H. A., & Pasandidehfard, M. (2024). Innovative optimization of parabolic cavitators: Improving hydrodynamic efficiency and supercavity qualitycavitatio. *Physics of Fluids*, *36*(10). https://doi.org/10.1063/5.0231369

Fernández García, I., González Perea, R., Moreno, M. A., Montesinos, P., Camacho Poyato, E., & Rodríguez Díaz, J. A. (2017). Semi-arranged demand as an energy saving measure for pressurized irrigation networks. *Agricultural Water Management*, *193*, 22–29. https://doi.org/10.1016/j.agwat.2017.07.025

Furman, W. B. (2020). *Continuous Flow Analysis*. Theory and Practice. CRC Press. https://doi.org/10.1201/9781003064992

Georgiadis, N. J., Yoder, D. A., & Engblom, W. A. (2006). Evaluation of modified two-equation turbulence models for jet flow predictions. *AIAA*

Journal, *44*(12), 3107–3114. https://doi.org/10.2514/1.22650

Groß, T. F., Pöttgen, P. F., & Pelz, P. F. (2017). Analytical approach for the optimal operation of pumps in booster systems. *Journal of Water Resources Planning and Management*, *143*(8). https://doi.org/10.1061/(ASCE)WR.1943-5452.0000776

Heo, T. S., Choi, S. W., & Sang, J. H. (2016). Booster pump control method (Korean Patent No. KR101672129B1). Korean Intellectual Property Office. Issued November 4, 2016. https://patents.google.com/patent/KR101672129B1/en

Hossain, J., Kadir, A. F., Hanafi, A. N., Shareef, H., Khatib, T., Baharin, K. A., & Sulaima, M. F. (2023). A review on optimal energy management in commercial buildings. *Energies*, *16*(4), 1609. https://doi.org/10.3390/en16041609

Khramshin, V., Karandaev, A., & Radionov, A. (2014). Energy Saving in the Hot Water Supply Systems of Buildings. *Applied Mechanics and Materials*, *698*, 815–821. https://doi.org/10.4028/www.scientific.net/AMM.698.815

Koor, M., Vassiljev, A., & Koppel, T. (2016). Optimization of pump efficiencies with different pumps characteristics working in parallel mode. *Advances in Engineering Software*, *101*, 69–76. https://doi.org/10.1016/j.advengsoft.2015.10.010

Li, X., Zhou, H., Wei, Z., & Zhu, Z. (2024). Interstage transmission and differential analysis of pressure fluctuations in multistage centrifugal pump-as-turbine. *Physics of Fluids*, *36*(5). https://doi.org/10.1063/5.0201871

Luna, T., Ribau, J., Figueiredo, D., & Alves, R. (2019). Improving energy efficiency in water supply systems with pump scheduling optimization. *Journal of Cleaner Production*, *213*, 342–356. https://doi.org/10.1016/j.jclepro.2018.12.190

Makaremi, Y., Haghighi, A., & Ghafouri, H. R. (2017). Optimization of pump scheduling program in water supply systems using a self-adaptive NSGA-II; a review of theory to real application. *Water Resources Management*, *31*(4), 1283–1304. https://doi.org/10.1007/s11269-017-1577-x

Midiani, L. P. I., Irawan, I. M. D., Bangse, K., & Gunung, I. N. (2023). Design of clean water booster pump for high-rise buildings. *LOGIC : Jurnal Rancang Bangun Dan Teknologi*, *23*(3), 203–211. https://doi.org/10.31940/logic.v23i3.203-211

Müller, T. M., Leise, P., Meck, T., Altherr, L. C., & Pelz, P. F. (2019). *Systemic optimization of booster stations - from data collection to validation*. 4th International Rotating Equipment Conference, Wiesbaden, Germany. https://doi.org/10.26083/tuprints-00020901

Nguyen, D. A., Lee, H. J., Kim, S., Choi, B. L., Choi, D. H., Kim, G. S., Sun, S., & Kim, J. H. (2024). Multiobjective hydraulic optimization of the diffuser vane in an axial flow pump. *Physics of Fluids*, *36*(7). https://doi.org/10.1063/5.0214940

Nikolenko, I. V., & Ryzhakov, A. N. (2020). *Parallel operation mode optimization of different-type centrifugal pumps of a water supply booster pumping station*. 2020 International Conference on Dynamics and Vibroacoustics of Machines (DVM), 1–6. https://doi.org/10.1109/DVM49764.2020.9243886

Nogueira Vilanova, M. R., & Perrella Balestieri, J. A. (2014). Energy and hydraulic efficiency in conventional water supply systems. *Renewable and Sustainable Energy Reviews*, *30*, 701–714. https://doi.org/10.1016/j.rser.2013.11.024

Østergaard, P. A., & Andersen, A. N. (2016). Booster heat pumps and central heat pumps in district heating. *Applied Energy*, *184*, 1374–1388. https://doi.org/10.1016/j.apenergy.2016.02.144

Pedersen, G. K. M., & Yang, Z. (2008). *Efficiency optimization of a multi-pump booster system*. Proceedings of the 10th Annual Conference on Genetic and Evolutionary Computation, 1611–1618. https://doi.org/10.1145/1389095.1389400

Pinto, J. M., Joly, M., & Moro, L. F. L. (2000). Planning and scheduling models for refinery operations. *Computers & Chemical Engineering*, *24*(9–10), 2259–2276. https://doi.org/10.1016/S0098-1354(00)00571-8

Rakibuzzaman, M., Kim, H. H., Kim, K. W., Suh, S. H., & Bae, Y. S. (2022). A study on booster pump system with flow sensor for individual flow control method. *Journal of Applied Fluid Mechanics, 15*(3), 889–900. https://doi.org/10.47176/JAFM.15.03.33153

Rakibuzzaman, M., Kim, H. H., Suh, S. H., Islam, M. D., & Zhou, L. (2024). Effects of cavitation and erosion on submersible drainage pumps: A numerical study. *Physics of Fluids*, *36*(8). https://doi.org/10.1063/5.0223126

Weber, J. B., & Lorenz, U. (2017). Optimizing booster stations. *Proceedings of the Genetic and Evolutionary Computation Conference Companion*, 1303–1310. https://doi.org/10.1145/3067695.3082482

Yang, Z., & Borsting, H. (2010). *Optimal scheduling and control of a multi-pump boosting system*. 2010 IEEE International Conference on Control Applications, 2071–2076. https://doi.org/10.1109/CCA.2010.5611177

Ye, S., Li, X., Zhu, Z., Li, L., & Lin, T. (2022). Numerical study of the energy flow characteristics of multi-stage pump as turbines. *Processes*, *10*(12), 2488. https://doi.org/10.3390/pr10122488

Zhang, H., Xia, X., & Zhang, J. (2012). Optimal sizing and operation of pumping systems to achieve energy efficiency and load shifting. *Electric Power Systems Research*, *86*, 41–50. https://doi.org/10.1016/j.epsr.2011.12.002