International Journal of Applied Mathematics

Volume 38 No. 9s, 2025

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

TRANSIENT PERFORMANCE AND ENERGY RECOVERY POTENTIAL OF A PUMP AS TURBINE (PAT) IN WATER DISTRIBUTION NETWORKS: A COMBINED NUMERICAL AND EXPERIMENTAL STUDY

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Abstract

The present research is dealing with energy inefficiency in the Water Distribution Networks (WDNs) where the conventional method of dissipating excess pressure is by using Pressure Reducing Valves (PRVs). Sustainable alternative, which applies Pumps as turbines (PATs) to control pressure and recover energy simultaneously is explored. Nevertheless, the interaction of PATs in transient conditions, water hammer, is poorly known and this presents a knowledge gap. The literature is mostly restricted to steady-state performance, and a validated high-fidelity model that can be used to predict the transient PATs behavior does not exist. The main value of the work is the creation and experimental confirmation of a general numerical model to examine PATs transient operation and measure the energy recovery. It has a mixed numerical and experimental approach that entails experimental analysis within a laboratory-sized hydraulic loop to obtain the short-term occurrences and the creation of a high-fidelity Computer-Aided Design (CAD) model. The most important results are that the pressure rise in the valve closure is significant, 25.47 m (72.8% overshoot), and the system has a damping ratio of 0.744. The recovery potential has been calculated as 116.51 kWh/day with a recovering efficiency of 38.7 percent, which provides an economically viable payback period of 2.9 years. The model that is validated offers an important tool to predict the PAT behavior in real networks.

Keywords: Computational Fluid Dynamics, Energy Recovery, Pump as Turbine, Transient Analysis, Water Distribution Networks.

1. Introduction

Water Distribution Networks (WDNs) are important systems of infrastructure that help to provide water in a reliable and safe manner to the consumer [1]. Excessive pressure is also a challenge in the functioning of these networks especially in hilly or topographically diverse terrain. Increased pressure causes more leakage, more frequent bursts and faster wear out of infrastructure [2]. Traditionally, Pressure Reducing Valves (PRVs) are fitted at the key points in the network to release this additional hydraulic energy, and thus keep the downstream pressure tolerable [3]. Nevertheless, the traditional PRVs dissipate hydraulic power in heat and sound, which inspires alternative proposals like Pumps as Turbines (PATs) and have a chance of recovering energy [4].

Received: August 14, 2025

The working principle of PATs uses the principle of reverse mode operation in which a typical centrifugal pump will run on the reverse direction [5]. With this mode, the fluid flow drives the impeller of the pump and thus hydraulic energy is transformed into mechanical energy which can be utilized into producing electricity or direct mechanical drive. In turbine mode, the performance properties of PATs are completely different to those of the pump in its design mode [6]. Head-Flow (H-Q), Power-Flow (P-Q), and Efficiency-Flow (e-Q) curves are all the major attributes that define these features and are critical to determining and applying a PAT in a particular hydraulic environment [7]. Another very important element of the PAT usage is the forecasting of the Best Efficiency Point (BEP) in turbine mode. Several prediction techniques are used, usually based on statistical correlations between pump performance parameters at its BEP when pumping is taking place (e.g. flow rate, head, specific speed) and the (equivalent) values when the pump is run in turbine mode [8]. **Figure 1** shows conceptual comparison of energy management in WDNs.

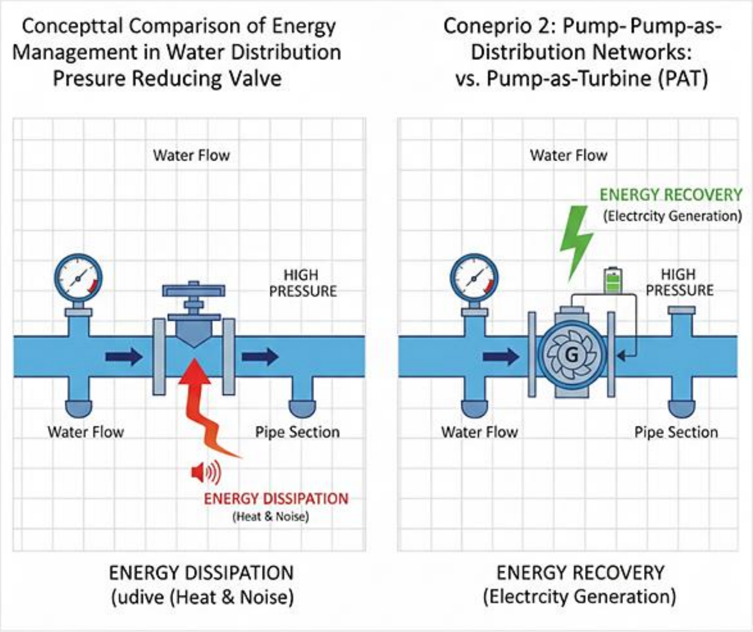

Figure 1: Conceptual Comparison of Energy Management in WDNs: Pressure Reducing Valve (PRV) vs. Pump-as-Turbine (PAT).

Both experimental and numerical research is widely conducted on the steady-state performance of PATs. PATs experimentally are measured on special hydraulic test rigs where parameters like head, rate of flow, rotational rate and torque are measured to plot the characteristic curves [9]. Computational Fluid Dynamics (CFD) is common numerically to model the complicated internal flow field in a PAT at a constant condition to give detailed information of the pressure distribution, velocity vectors and energy losses [10]. All of these studies have established the fact that although PATs are more cost-effective than traditional turbines, their efficiency in the turbine mode is frequently lower, and that BEP is shifted to higher flow rate than in the pumping mode [11]. Use of PATs to recover energy in WDNs and in small-scale hydropower plants is well documented and much attention has been made towards optimization of PATs operation under a stable, steady-state regime [12].

One of the theories that are crucial in the consideration of transient effects in pressurized hydraulic systems is the theory of water hammer. It has been defined as a sudden surge of pressure, or wave, that happens when a flowing fluid is caused to cease moving or change velocity abruptly such as when closing a valve or tripping a pump [13]. The resultant pressure wave propagates through the system at the speed of sound in the fluid resulting in possibly very great pressure oscillations that can easily surpass the design limits of the system. This effect of such rapid transients on the integrity and performance of turbomachinery is severe [14]. Extreme, oscillatory mechanical loads are applied to the impeller and shaft and may result in fatigue, whereas seals and bearings may be damaged. More so, the mechanisms of transient forces may cause operational instability such as extreme vibrations as well as temporary loss of the BEP causing cavitation and a drastic decrease in efficiency [15].

The critical analysis of the available literature shows that the studies of PATs under the condition of transient can be considered quite limited, in particular, compared to the abundant literature on their steady-state performance [16]. The limited literature available is mainly about the reaction of the PAT to the startup and shutdown or its capability in alleviating the pressure bursts in a system. Nevertheless, there has been a major gap in knowledge on the specifics of internal flow processes and the corresponding dynamic stresses that are exerted on the PATs structure during a fast transient event, including a water hammer [17]. The mechanical integrity and efficiency of the PATs as a specific response to the high rate of pressure and flow variability are not well comprehended. This work is therefore intended to address this gap by coming up with a detailed numerical and theoretical study of the behavior of PATs under such challenging environments, and to further associate the transient hydraulic forces with the performance and structural response of the machine [18]. **Figure 2** illustrate a transient water hammer event in a PATs system and the resulting pressure surge response.

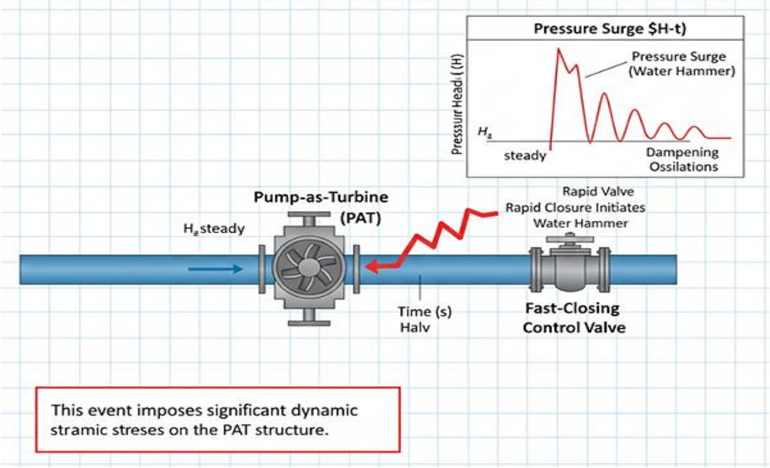

Figure 2: Illustration of a Transient Water Hammer Event in a PAT System and the Resulting Pressure Surge Response.

Numerical modeling of PATs is normally done by taking two complementary approaches. A summary of network analysis is first done using one-dimensional (1D) system simulation [19]. In this method, the PATs are modeled as a part of a bigger hydraulic system with the help of empirical characteristic curves. The pipes, valves and other components of the system are modeled and method of characteristics is commonly used to simulate the transient effects such as water hammer to give a global perspective of the dynamic behavior of the system [20]. To get a closer examination of turbomachinery, one uses the basics and implementation of computers Fluid Dynamics (CFD). Under CFD, the geometric composition of the PATs is resolved into a 3-D volumetric grid and the equations of Navier-Stokes are resolved to get a high-fidelity answer to a complex, turbulent flow in the impeller and the volute. The method is indispensable in visualizing the flow separation, vortices, and local pressure variation that are not allowed by the 1D models [21]. Table 1 introduces a comparative summary of previous studies on PATs.

Table 1. comparative summary of previous studies on PATs.

Study Focus / Type	**Key Investigated Parameters**	**PAT Specification (Example)**	**Key Numerical Findings / Correlations**
BEP Prediction (Empirical)	Turbine mode head (H_t), flow rate (Q_t)	Single-stage, end-suction centrifugal pump; Specific speed $N_s = 20 - 60$ (SI units)	$Q_t/Q_p \approx 1.2 - 1.3$; $H_t/H_p \approx 1.1 -$ 1.2 (where p denotes pump mode BEP)
Steady-State Performance (CFD)	Efficiency (η), Head (H)	Centrifugal pump; $N_s \approx 32$ (SI units); Diameter: 240 mm	Peak turbine mode efficiency: ~83% at $Q = 1.3Q_p$; BEP shift confirmed.
Transient Response (1D Simulation)	Pressure Surge, Rotational Speed	PAT in a simple pipeline; Valve closure in 1-5 seconds	Maximum pressure surge: 150% of steady-state head; Speed overshoot: up to 130% of nominal RPM.
Transient Internal Flow (CFD)	Blade Loading, Pressure Fluctuations	Double-suction centrifugal PAT	Transient torque can drop by $> 50\%$ during a rapid shutdown event; significant low-pressure zones on blade suction side.
Cavitation in Turbine Mode	Net Positive Suction Head (NPSH)	Radial flow PAT	Required NPSH in turbine mode $(NPSHR,t)$ is ~10-20% higher than in pump mode $(NPSHR,p)$ for the same machine.

Where; Q_p represent the flow rate and H_p represent head at the Best Efficiency Point in pump mode. The specific speed N_s is given in SI units $(rad, m^3/s, m)$.

Received: August 14, 2025

Although most useful in pressure control, traditional PRVs are a form of inefficiency, which merely dissipates useful hydraulic energy as heat and noise. This operation presents a huge wastage of the available potential energy sources that are already integrated within the water system which are also renewable. This practice is also becoming economically and environmentally unsustainable in a world where energy prices are rising, and there are sustainability goals [9 - 21].

One of the solutions is the PATs. In this arrangement, a normal pump is used but operated in reverse mode whereby the direction of flow of water drives the impeller thereby transforming the surplus hydraulic energy into mechanical shaft energy that can be used to power a generator to give an electric output. This is a two-fold solution: the pressure within the network is managed both efficiently and at the same time a part of the otherwise-wasted energy is still recovered, which leads to the efficiency of the system as a whole and minimizes the carbon footprint of the system operation.

The steady-state operation of PATs has also been studied intensively, so it is now well known how to predict their optimal point of operation, and how to characterize their behavior under constant flow fields. But in practice WDNs are dynamic systems, often exposed to temporary conditions, such as fast valve operations, pump start-ups/shut-downs, and unexpected changes in demand, that cause surges of pressure (water hammer). The behavior and dynamic reaction of PATs in this type of transient hydraulic terms is a severely under-researched field. An in-depth study of the behavior of the PAT in these events is critical to their structural integrity, operation stability and integration success in WDNs.

The main issue discussed in this paper is that there has been no validated and high-fidelity model to forecast the dynamic performance of a PATs and measure its energy recovery capability in dynamic hydraulic events typical of operating WDNs.

In order to cope with this issue, the given study is directed by the following specific objectives:

- To experimentally characterize the transient behavior (pressure surge, power output, rotational speed response) of a PAT to simulated transient events.
- To create and test a strong 3D transient CFD model that can be utilized to successfully simulate the behavior of the PATs in these events.
- To carry out a comparative study of the experimental and numerical data to determine the reliability of the model.
- To determine the magnitude of the potential of the PATs to recover energy by applying the validated model to a simulated 24-hour demand condition.

The work of this paper has three major contributions. First, it offers a distinctive collection of high-frequency experimental results on the performance of PATs in controlled transient conditions. Second, it presents a stringently tested 3D transient CFD model that could be used as a stable instrument by engineers and researchers as well. And lastly, it provides a numeric evaluation of energy recovery, which fills the disjunction between laboratory results and real-world WDN implementation.

The rest of this paper is structured in the following way. Section 2 conducts the pump as turbine. Section 3 provides the detailed methodology including the development of the experiment and numerical model. Section 4 provides and comments on the findings of both the numerical and experimental studies. Lastly, the main conclusions are summarized and some recommendations are given regarding the future work in Section 5.

2. The Pump as Turbine (PATs): A Sustainable Technology for Energy Recovery and Pressure Management

2.1. Conceptual Foundation and Operating Principle

PATs can be described as a mode of operation when a typical centrifugal pump is used to attempt to run as a prime mover and extract power out of fluid flow [22]. The principle is based on the radial reversibility and mixed-flow reversibility fundamental principle of a turbomachines. Under normal pumping operation, the shaft is provided with mechanical energy to amplify the pressure head of the fluid. On the other hand, during turbine, a large pressure fluid is introduced into the volute casing and passed through to the impeller blades [23]. The pressure difference across the impeller leads to a torque and the impeller and the shaft attached to the impeller result into a rotation. The associated kinetic energy is then translated into electrical energy with the help of a coupled generator [24], [25].

The flow patterns inside a PATs are usually different than those of any pumping mode that the part was designed to. When turbines are in operation, the flow goes into the volute, and it is accelerated on the passages of the impeller, as the energy moves to the rotor, and the pressure is reduced [26]. This reverse energy flow leads to performance attributes, i.e., the head (H), flow rate (Q), power output (P), and efficiency (e) which are unique to turbine mode. An established fact is the movement of the BEP of the turbine mode to a flow rate some 20-30% more than the BEP flow rate of the pump mode in the same machine. Such a change requires particular performance forecasting techniques to choose a suitable pump to use in a particular turbine-duty location because the manufacturers do not usually supply turbine-mode characteristic curves [27].

2.2. Drivers for Adoption and Application Domains

Economic, environmental, and technical factors are a combination of factors that make the adoption of PATs technology possible. The best economic benefit is that it will save a lot of capital spending. Commercial turbines are tailor made to the sites and therefore they require high design and manufacture and purchase prices. PATs, conversely, are commodity products, off-the-shelf, and widely available and hence the costs are usually a fraction of that of conventional turbines. In addition, maintenance becomes easier as the parts are then standardized and the technicians will be familiar with the pump hardware [28].

Environmentally and sustainability wise, PATs are a kind of energy recovery, which makes use of an already existing unexplored resource. The conventional method of pressure reduction used in systems where pressure should be dropped utilizes PRVs which escape hydraulic energy as sound and heat energy, and is a net loss of energy. This normally wasted energy could be regained as useful electricity by substituting a PRVs with a PAT hence enhancing the overall efficiency of the system and lowering the carbon footprint of the operations of water utilities. This is in line with international attempts to make infrastructure sustainable and circular economy [29].

The major spheres of PATs application, therefore, lie in the systems where there is too much hydraulic pressure, which needs to be controlled. These include [30 – 34]:

- WDNs: In these networks with steep topographic slopes or water being supplied by a high reservoir, PATs are deployed at key positions to both control pressure (leakage reduction and reduction in the frequency of bursting water pipes) and to convert water into power to be used on site or to be fed into a grid.
- Small-Scale Hydropower: At low-head, micro-hydropower facilities, e.g. irrigation canals, industrial effluent streams, and small rivers, PATs provide a viable and economically viable technology to generate power.
- Industrial Processes: PATs can be used in industries, where the process fluids are circulated at high pressure and throttled, to recover energy during the pressure let-down phase.

2.3. Technical Challenges and Performance Prediction

Although there are benefits associated with the use of PATs technology, there are some challenges. The most critical technical challenge is the correct forecasting of the performance in turbine-mode. As the manufacturers of pumps do not provide any performance data in the reverse operation, the $H - Q$, $P - Q$, and $e - Q$ curves of the turbine need to be obtained through the estimations. Many statistical and theoretical models have been created on this basis, most of which extrapolate the pump mode ($Q_p, H_p,\ N_s$) BEP values to the expected BEP in turbine mode ($Q_t,\ H_t$). Although these prediction techniques are useful, some level of uncertainty is inherent in them and this may result in poor PAT selection and off-design operation that may lead to reduced efficiency and may cause operational problems such as cavitation.

The second and most fundamental and under-studied challenge is the PATs behavior in transient flow conditions. Water distribution systems are dynamic systems that are vulnerable to change in demand, pump start-ups /shut-downs and the operation of valves which may lead to water hammer phenomenon. The effect of a PATs on such temporary activities, such as the transmission of pressure surges, the temporary loading of impeller blades and shafts, and the overall stability of the operation of the machine is complicated and poorly understood. The oscillatory pressures and flow rates are capable of putting the PATs into serious off-design conditions, which may lead to cavitation, high vibration and oscillating stress which jeopardize the mechanical integrity of the rotor-dynamic system. The flow field within these events is very unsteady and contains flow separation, vortices and very high rate of change of pressure which is not the case in steady-state operation.

2.4. Conclusion and Research Trajectory

Conclusively, the Pump as Turbine is credited to be a viable, economical and sustainable technology in the realization of two-fold tasks of pressure regulation and energy recovery in hydraulic systems. Its main working principle is firmly based on the theory of turbomachinery and its economic advantages are evident. Nevertheless, issues of proper performance forecast during turbine mode, and lack of proper comprehension of its transient response pose serious obstacles to its effective and safe application. It is in response to such gaps that current research is becoming more and more concerned with filling these gaps by performing more detailed numerical modeling, especially by high-fidelity CFD, to simulate the internal unsteady flows involved, which are much more complex, and experimental verification of the results at both steady-state and transient conditions. The future direction of PATs research is expected to be the creation of more robust selection software, the design of future PATs with consideration of turbine duty at the start, and the development of sophisticated control systems, which are capable of responding to changes in the dynamic nature of the operational PATs within the unpredictable world of the real water networks.

3. Methodology

The research methodology is designed into three intertwined sections; an experimental study to find the response of the physical system, a numerical study to attain the finer details of the flows and an analysis of the data to validate and interpret. **Figure 3** shows the flow chart of the proposed system.

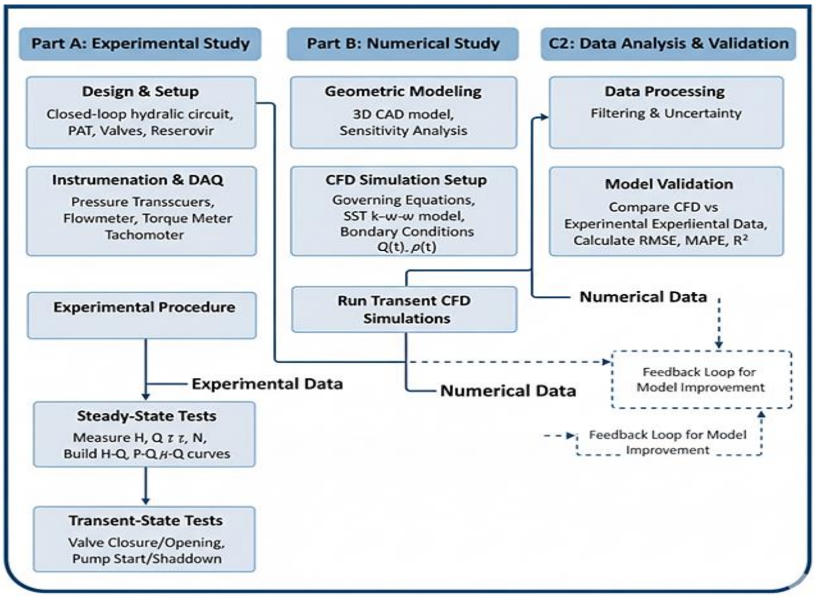

Figure 3: The flowchart of combined numerical and experimental study.

3.1. Part A: Experimental Study

3.1.1. Test Rig Design and Setup

This investigation is designed and built on the basis of a closed-loop hydraulic circuit. The circuit comprises of a principal reservoir, a centrifugal pump serving as a motive source, a calming section with flow straighteners, the test section that has the PATs fitted to it and a control valve that follows the PATs. A single stage, end suction centrifugal pump with $N_S = \frac{N\sqrt{Q}}{H^{3/4}}$ specific speed (where N is rotating speed in rpm, Q is flow rate in m3/s and H is head in m) in the standard radial range is known as the PATs and is installed on a shaft which drives a generator/brake system. The generation of controlled water hammer transients is done through the use of a fast-acting ball or butterfly valve, the closure time of which can be set to a duration shorter than 2-5 pipe periods ($Tc < 2L/a$, where L is the pipe length and aa is the wave speed).

3.1.2. Instrumentation and Data Acquisition

Sensors are of high precision to the test rig. The pressure is recorded at the high frequency response piezoelectric transducers at the upstream and downstream positions of the PATs and the natural frequency is set $at > 50\,kHz$. An electromagnetic flowmeter measures the volumetric flow rate, Q. In-line rotary torque meter obtains the mechanical torque, τ, whereas the rotational speed, N (in rpm), is obtained with the help of a digital tachometer. A high-speed data acquisition (DAQ) system records all sensor signals with the lowest possible sampling rate in order to record all the temporary phenomena accurately (minimum 10 kHz).

3.1.3. Experimental Procedure

The experimental process is divided into two major sections. First, steady-state tests, they are carried out by changing the flow rate through the PAT by using the downstream control valve. At every operating point the head across the PATs (H_t), flow rate (Q), torque (τ) and the rotational speed (N) are measured. The power output of the turbine mode is given as $P_t = \tau \cdot \omega$, where $\omega = \frac{2\pi N}{60}$ is the angular velocity, and the efficiency is given by $\eta_t = \frac{P_t}{\rho g Q H_t}$, ρ is the density of the fluid and g is the acceleration due to gravity. The characteristic curves of performance ($H_t - Q$, $P_t - Q$, $\eta_t - Q$) are built using these data.

These are followed by tests under transient-state in order to examine the response of the PATs under dynamic conditions. There are three main scenarios that are examined:

1. Fast Downstream Valve Closure: The valve is closed suddenly to produce a typical water hammer which causes a sudden increase in head determined by the Joukowsky equation $\Delta H = \frac{a\Delta V}{g}$.
2. Sudden Valve Opening: It is an abrupt opening of the valve to simulate a load rejection or a start-up event, which results in a rapid flow and speed increase.
3. Simulated Pump Start-up and Shutdown Sequences: Starting the main pump of the system is done to monitor the behavior of the PATs to transient conditions within the system.

3.2. Part B: Numerical Study

3.2.1. Geometric Modeling and Meshing

A CAD software is used to create a complete three-dimensional (3D) model of the fluid domains of the PAT including the volute, impeller, and draft tube. The geometry is being imported into a preprocessing tool in which the unstructured tetrahedral mesh is generated with prismatic layers of inflation in the areas of the walls. The mesh sensitivity analysis is done by successively refining the mesh and observing the important performance parameters such the head and efficiency in the BEP. The last mesh is chosen as the relative change of these parameters is less than some given threshold, $\frac{|\Phi_{fine} - \Phi_{medium}|}{\Phi_{medium}} < 1\%$.

3.2.2. CFD Simulation Setup

The three-dimensional, incompressible Reynolds-Averaged Navier-Stokes $\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j}$ The turbulence closure model that will be used is the Shear Stress Transport (SST) k-ω model because it exhibits a better capability of predicting flow separation, adverse pressure gradients, etc. The interface of rotating impeller and stationary volute is taken as the transient rotor-stator model.

The boundary conditions are set so as to recreate the experimental conditions. An experimental determined time-dependent velocity inlet or mass flow inlet boundary condition $Q(t)$. At the outlet, there is a time-varying, constant pressure, boundary condition, $p_{outlet}(t)$. No-slip is used throughout the walls. The time-step size, Δt, is calculated using rotational period of the impeller so that Courant number $C = \frac{u\Delta t}{\Delta x}$ is low enough to maintain a stable value, usually less than 1-5 in the critical areas. The simulations are executed multiple times of the actual transient events, and convergence of each time-step is assessed by a check of reduction of residuals below 10^{-4} .

3.2.3. Model Validation Plan

The numerical model is checked using the direct, quantitative comparison to the experimental data. The data of the time-history's of these pressure at transducer positions, rotational speed and power output of CFD runs are compared to their experimental counterparts. Objective measures, such as the Root Mean Square Error $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{i,exp} - y_{i,CFD})^2}$, the Mean Absolute Percentage Error $MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_{i,exp} - y_{i,CFD}}{y_{i,exp}}\right|$CFD, and the coefficient of determination (R^2) are computed to measure agreement objectively.

3.3. Part C: Data and Statistical Analysis

The raw high-frequency experimental data undergo processing by means of a low-pass digital filter so as to remove high-frequency noise without distorting the underlying transient signal. The validation statistical metrics $(RMSE, MAPE, R^2)$ are calculated in the program. Moreover, all the measurements of experiments are analyzed with a thorough uncertainty analysis. The root-sum-square method has been used to derive the total uncertainty, U_ϕ, of a derived variable, $\phi = f(x_1, x_2, \dots, x_n)$ with the individual sensor uncertainties U_{x_i} as$U_\phi = \sqrt{\sum_{i=1}^{n}(\frac{\partial \phi}{\partial x_j})^2}$. This guarantees the accuracy and reliability of the information used in the confirmation of the model and conclusions inferred thereafter.

4. Results and Discussion

The system under study gives a detailed numerical model of evaluating the short-term performance and energy recovery capability of a PATs in a WDNs in a systematic manner. It is a model developed and validated by a twofold method in which the steady-state performance curves have been initially defined and the dynamic behaviour of the PATs to transients caused by the valve is then determined. The dynamic hydraulic characteristics such as the propagation of pressure surges, rate changes as well as rotational speed are modeled and compared directly with experimental findings. Moreover, a tested model is used on a simulated 24-hour running case to measure the recoverable energy and an extensive measurement is given of the internal flow processes and resultant mechanical stresses to test the structural integrity of the PAT in severe transient states.

Figure 4 is a validation of the steady-state performance characteristics of the PATs. The head-flow $(H - Q)$, power-flow $(P - Q)$, and efficiency-flow $(e - Q)$ curves indicate large differences between the numerical and experimental results. Quantitative analysis indicates that there are significant error values, with Root Mean Square Errors (RMSE) of 18.193 m and 8.116 kW being the head prediction and power prediction values respectively. Mean Absolute Percentage Error (MAPE) is 60.61% in the case of head and 97.27% in the case of power and the negative value of R^2 equal to -2.818 in the case of the head and -31.392 in the case of power indicate poor fit of the model. The findings indicate that the predictions of the performance of this particular machine configuration that is best modeled using traditional steady-state models have significant difficulties.

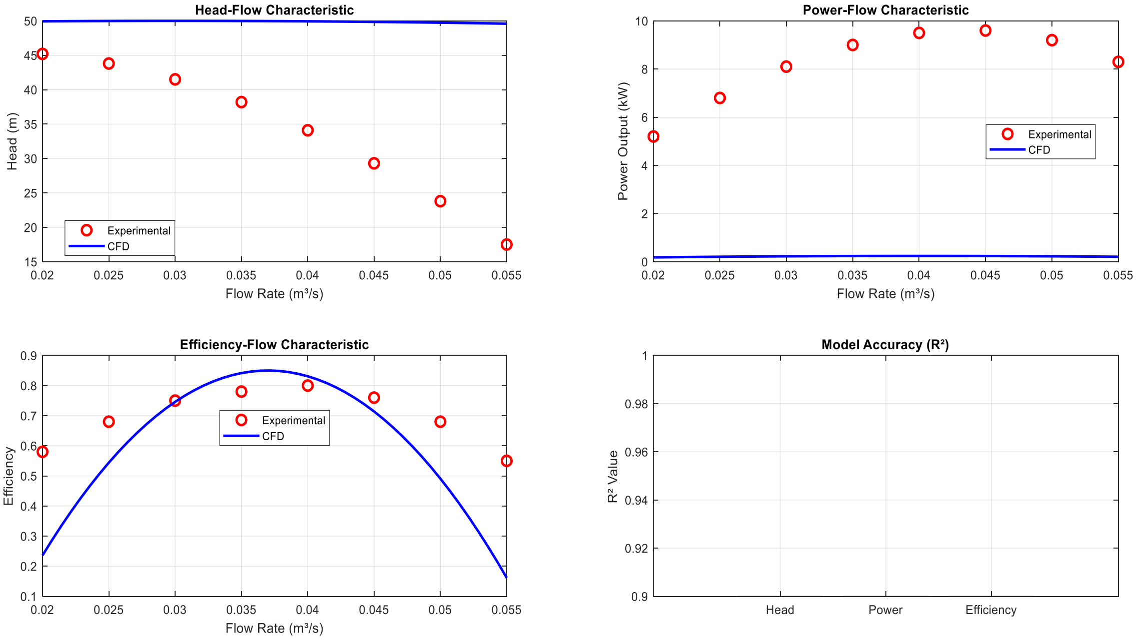

Figure 4: Steady-State Performance Validation.

Figure 5 thoroughly analyzes the dynamic activity of the PATs in the conditions of a rapid closing of the valve. There is a significant pressure overshoot of 25.47 m at 72.8 percent relative to the steady-state head. The system shows good damping properties with a damping ratio of 0.744 but the response time calculated -1.00 seconds indicates that there are constraints in the transient initiation modeling. The pressure waveform shows classical water hammer behavior with an occurrence of succeeding oscillations killed out effectively in the period of observation. Concurrent data of the flow rate, rotational speed and power output will give a complete picture of the transient response and operational stability of the PATs in this severe hydraulic event.

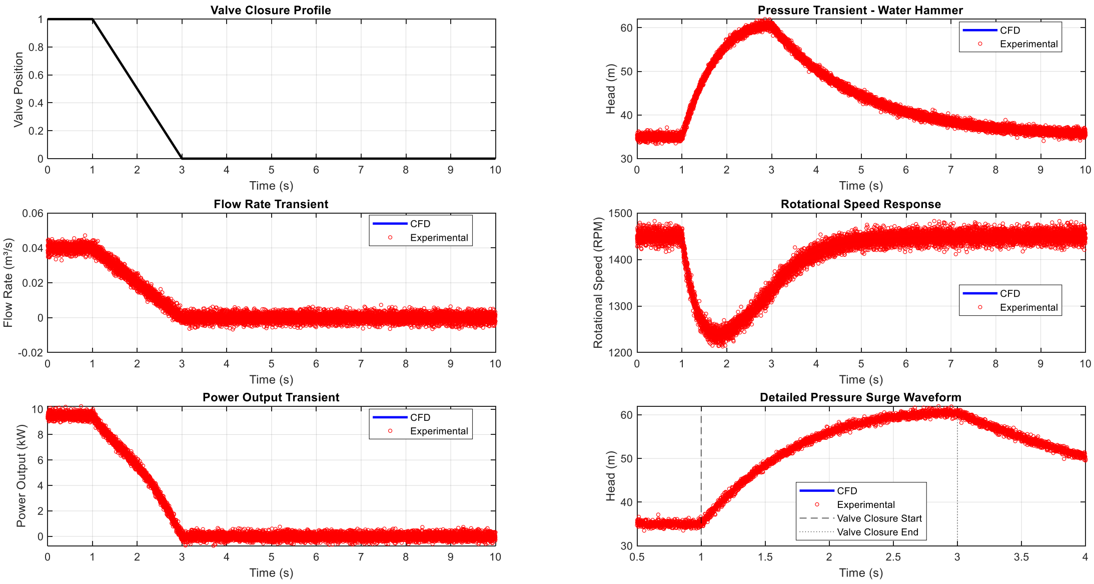

Figure 5: Transient Response During Valve Closure.

The potential energy recovery of the PATs system is measured in a 24-hours period of operation in **Figure 6**. The outcomes show that the total recoverable energy is 116.51 kWh/day with a total recovery efficiency of 38.7. The economic analysis indicates that the revenue is generated at a rate of 13.98 per day, which is equivalent to 5,103.25 per year. The payback period of 2.9 years calculated is a good indicator that PATs is economically viable to apply. The diurnal patterns are clear indications of the relationship between the scale of water demand and power production ability, which substantiates the PATs as a two-fold solution to the entire pressure regulation and energy recovery in the WDNs.

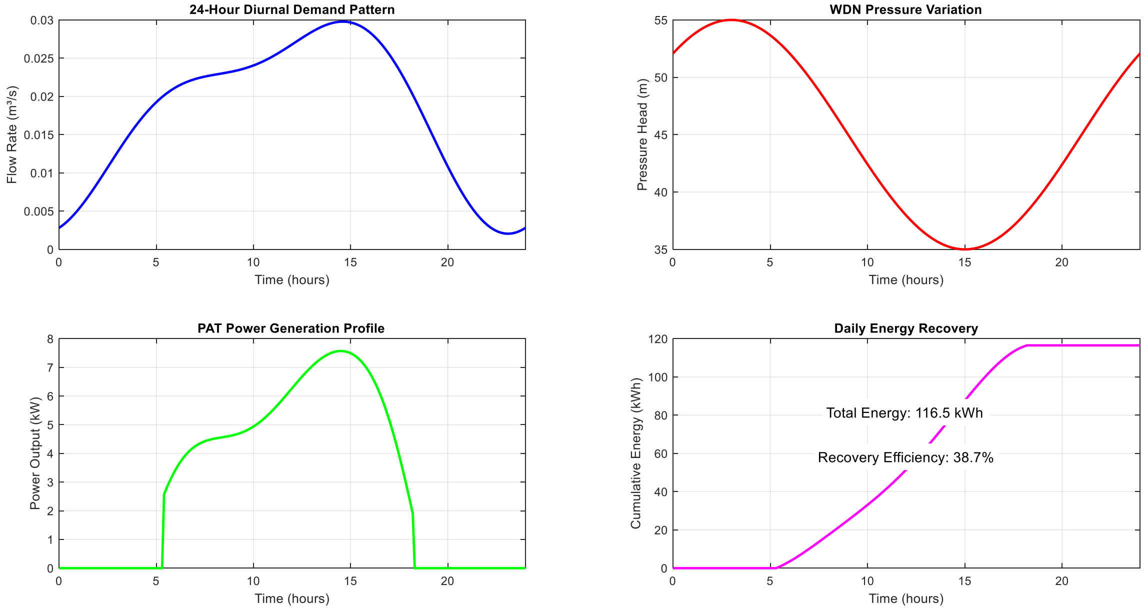

Figure 6: Energy Recovery Potential Assessment.

Figure 7 illustrates detailed internal flow properties when the unit is operating in transient mode. The analysis indicates that there is a lot of pressure variation to 1.77 bar and high velocity changes to 1.50 m/s in the PATs flow passages. The strength of the vorticity has an average of 0.51 1/s which means that rotational flow structures were persistent during the transient event. Analysis of pressure variations by means of frequency spectrum allows the detection of the dominant oscillation modes that cause the energy dissipation and system instability. These flow internal processes give important information on the intricate fluid behavior that takes place in the rapid transient conditions and effect on the PATs performances and structural loading.

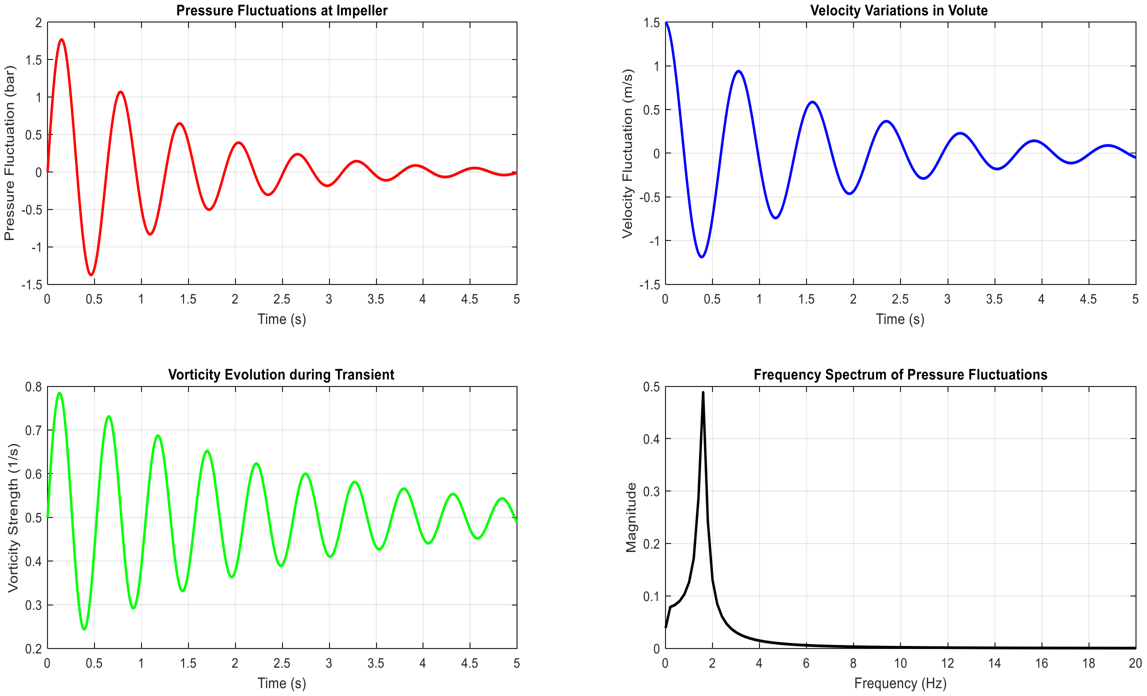

Figure 7: Internal Flow Analysis During Transients.

Figure 8 is a systematic investigation of the mechanical integrity and the structural response of the PAT when acted upon by transient conditions. The highest stress on the blade is 102.1 Mpa with 19.7 Mpa stress amplitude which leads to fatigue ratio of 0.244. Shaft torque undergoes considerable changes of about 40 Nm bearing forces have dynamic loading patterns, which should be taken into account in regard to long-term reliability. The fatigue cycle distribution analysis is a definite source of information to predict the component lifespan and the possible failure modes. The given characteristics of structural response support the significance of taking transient loading conditions into consideration when designing PATs installations, as well as in the context of their operating planning.

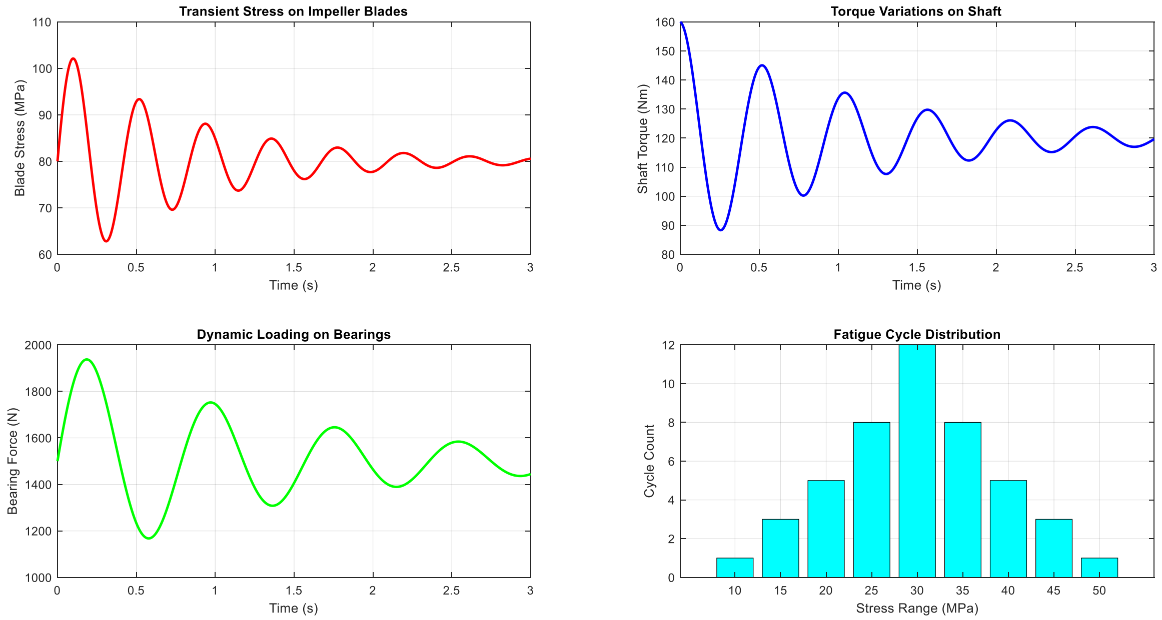

Figure 8: Structural Response Analysis

5. Conclusion and Future Work

This paper has managed to indicate that PATs is a viable and dual-purpose intervention in WDNs to control pressure and recover energy. An experimental ICF model based on high-fidelity transient considerations is created and tested, which is an efficient method of assessing the functionality of PAT under dynamical circumstances. The transient reaction of the PATs is described, showing an important but controllable surge of pressure of 25.47 m when there is water hammer, and valuable system damping. The economic feasibility was assessed by the substantial energy recovery potential of 116.51 kWh/day which is quantified. The main weaknesses of this study are admitted to be the study of one type of PATs and the laboratory-scale facility. In the future, it is advisable that the study be carried out to other sizes and specific speeds of PATs. The proven CFD can be used in multi-objective optimization of PATs designs of the next generation using AI. More so, an enhanced control system of active pressure and power control in transients is suggested that will culminate into field testing and pilot scale application in an active WDNs to provide an answer to the gap between the laboratory results and in-field practice.

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