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Experimental evaluation of energy recovery in a hydraulic braking system using accumulator-based storage

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ABSTRACT

This study presents the experimental evaluation of a hydraulic braking system equipped with an energy recovery mechanism based on a pressure-accumulator. The aim was to quantify the effectiveness of regenerative braking through comparative tests under three accumulator pre-charge pressures: 500 psi, 800 psi, and 1000 psi. The experimental setup included a custom-built data acquisition system that recorded the dynamic behavior of the system during deceleration phases, with and without the accumulator engaged. The power recovered was assessed by calculating the area under the energy-time curve using numerical integration techniques. Results indicate that the inclusion of the hydraulic accumulator reduced the total energy dissipated by up to 15.24% at 500 psi. As pressure increased, energy recovery efficiency slightly declined, reaching 14.43% at 800 psi and 13.19% at 1000 psi, likely due to internal hydraulic losses and early saturation of the accumulator. These findings demonstrate the technical viability of hydraulic energy recovery systems in mechanical braking applications and highlight the importance of optimal pressure selection for maximizing performance.

Keywords: Hydraulic energy recovery, Regenerative braking, Accumulator systems, Experimental evaluation, Braking energy

1. Introduction

Energy efficiency has become a fundamental axis for the development of sustainable technologies in the transportation and industrial sectors [1]. In this context, braking energy recovery systems have emerged as a key strategy to capture kinetic energy that is traditionally dissipated as heat during deceleration [2]. When properly recovered, this energy can be stored and reused, improving the overall energy performance of systems and contributing to a reduction in environmental impact.

Currently, two technological approaches dominate this field: systems based on electrical storage using batteries or ultracapacitors, and hydraulic systems that employ pressure accumulators. Recent studies have reported that electric-based systems can achieve energy recovery efficiencies between 60% and 70% in light urban vehicles while hydraulic systems—especially in industrial and heavy-duty transport applications [3]—can reach efficiencies ranging from 30% to 45%, standing out for their rapid response capabilities and high power density.

Unlike electric systems, hydraulic regeneration offers significant advantages in high-frequency operating cycles, enabling faster charge-discharge sequences and lower component degradation. Moreover, research by Abe [4] has shown that implementing regenerative braking systems can lead to energy savings of up to 20% in controlled environments, while in railway applications

Motivated by these advances, the present study aims to design, construct, and experimentally evaluate a braking energy recovery system based on a hydraulic circuit. Through the development of a laboratory-scale prototype, this work seeks to determine the energy efficiency achieved under different load conditions and assess the technical feasibility of this technology for application in transportation systems and industrial machinery. The study aims to provide experimental evidence to support the growing body of research advocating the use of hybrid and alternative systems for intelligent energy management in sustainable mobility.

2. Frame of reference

2.1. Theoretical and conceptual framework

Regenerative braking is a process that enables the capture of a portion of the kinetic energy of a vehicle or machine during deceleration, transforming it into a storable and reusable form of energy. Traditionally, this energy was dissipated as heat through conventional braking systems, representing a significant loss of energy resources. Today, the application of energy recovery technologies not only enhances operational efficiency but also promotes environmental sustainability by reducing pollutant emissions.

Various technologies have been developed for this purpose, with electric and hydraulic systems being the most prominent. While electric systems employ motor-generators along with batteries or supercapacitors, hydraulic systems utilize pumps, hydraulic motors, and accumulators to capture and release energy in the form of fluid pressure.

2.1.1. Hydraulic accumulators

Hydraulic accumulators are devices that store energy in the form of fluid pressure using a compressed gas (typically nitrogen), which is separated by a membrane or piston. During braking, hydraulic fluid exerts pressure on the gas, thereby storing energy that can later be released to assist in traction or other system functions [5].

Among the advantages of accumulators are their high-power density, their ability to handle rapid charge-discharge cycles, and their extended lifespan under demanding operating conditions [6]. However, they have limitations regarding the volume of energy that can be stored, making them more suitable for applications requiring short bursts of recovered energy.

2.1.2. Energy efficiency and energy harvesting

The energy efficiency of a regenerative system is defined as the ratio between the recovered energy and the kinetic energy available at the beginning of the braking process. Studies report that modern electric systems can achieve efficiencies between 60% and 70%, while hydraulic systems, depending on their design and operating conditions, reach efficiencies ranging from 30% to 45%.

Energy regeneration is widely applied in electric and hybrid vehicles, heavy machinery, and railway systems. Its implementation not only improves system autonomy but also reduces component wear, enhances operational safety, and supports compliance with increasingly stringent environmental regulations.

Future trends point toward the integration of hybrid systems that combine hydraulic and electric energy recovery, leveraging the strengths of both storage technologies to maximize the overall efficiency of vehicles and industrial equipment.

2.2. State of the art

The development of hydraulic regenerative braking systems has received increasing attention over the past decade, particularly in heavy machinery and mass-transportation applications. In excavators and other industrial equipment, accumulator-based architectures have been extensively investigated and systematized, demonstrating their viability as a robust alternative to electric storage solutions [7].

Within this context, a variety of control strategies have been proposed to maximize recovery efficiency. Ning et al. [8]validated, through a dedicated test bench, a regenerative braking algorithm for parallel hydraulic hybrids, showing that adaptive optimization techniques can significantly enhance system performance. Similarly, Li et al [9] introduced a game-theory-based control scheme designed to balance vehicle stability with energy efficiency, achieving improvements over conventional approaches.

Intelligent methodologies have also been explored. Anh et al. [10] implemented a fuzzy-logic-based regenerative braking system in hydraulic configurations, reporting double-digit efficiency gains under standardized driving cycles such as WLTC, NEDC, and FTP. More recently, Ghanami et al. [11] proposed a hierarchical control framework for combined hydraulic–regenerative braking, emphasizing the simultaneous fulfillment of safety requirements and the maximization of recovered energy.

Railway applications represent another relevant domain. Hoo et al. [3] demonstrated that operational parameters such as train headways and track profiles directly condition the potential for energy recovery in third-rail DC systems.

Dual configurations have also emerged as a promising approach to extend the operational window of hydraulic energy storage. Jiang et al. [12] documented the application of a dual hydraulic system, in which an auxiliary module complements the main one to improve both energy transfer and recovery efficiency. In the same vein, Tyni et al. [6] examined electro-hydraulic hybrid architectures, concluding that coupling electrical and hydraulic systems alleviates stress on battery packs while maintaining the ability to deliver high instantaneous power.

Taken together, these studies underline a clear trend toward the integration of advanced control strategies and hybrid configurations, aiming to overcome the inherent storage and responsiveness limitations of conventional systems and to consolidate the adoption of hydraulic regenerative braking technologies in high-performance applications.

3. Research design

The development of this research project was based on an experimental approach, structured in three main phases: design, implementation, and validation of the braking energy recovery system using a hydraulic circuit. Each phase was carried out sequentially and in a dependent manner, ensuring technical consistency and the reliability of the results obtained.

The first phase, corresponding to the design of the hydraulic circuit, involved the creation of functional diagrams using specialized software. FESTO FluidSIM was employed for the graphical and symbolic representation of the hydraulic components (see figure 2), defining the connections between the hydraulic pump, hydraulic motor, pressure accumulator, and various flow control elements.

Figure 1. Hydraulic pump

Given the availability of a pre-existing test bench, the design was adapted to the specifications of the available electric motor and hydraulic pump. The hydraulic motor was then dimensioned accordingly, and a bladder-type accumulator with a capacity of 0.75 liters and a pre-charge pressure of 150 psi was selected. This choice was based on an optimization criterion that balanced component availability with the expected energy efficiency.

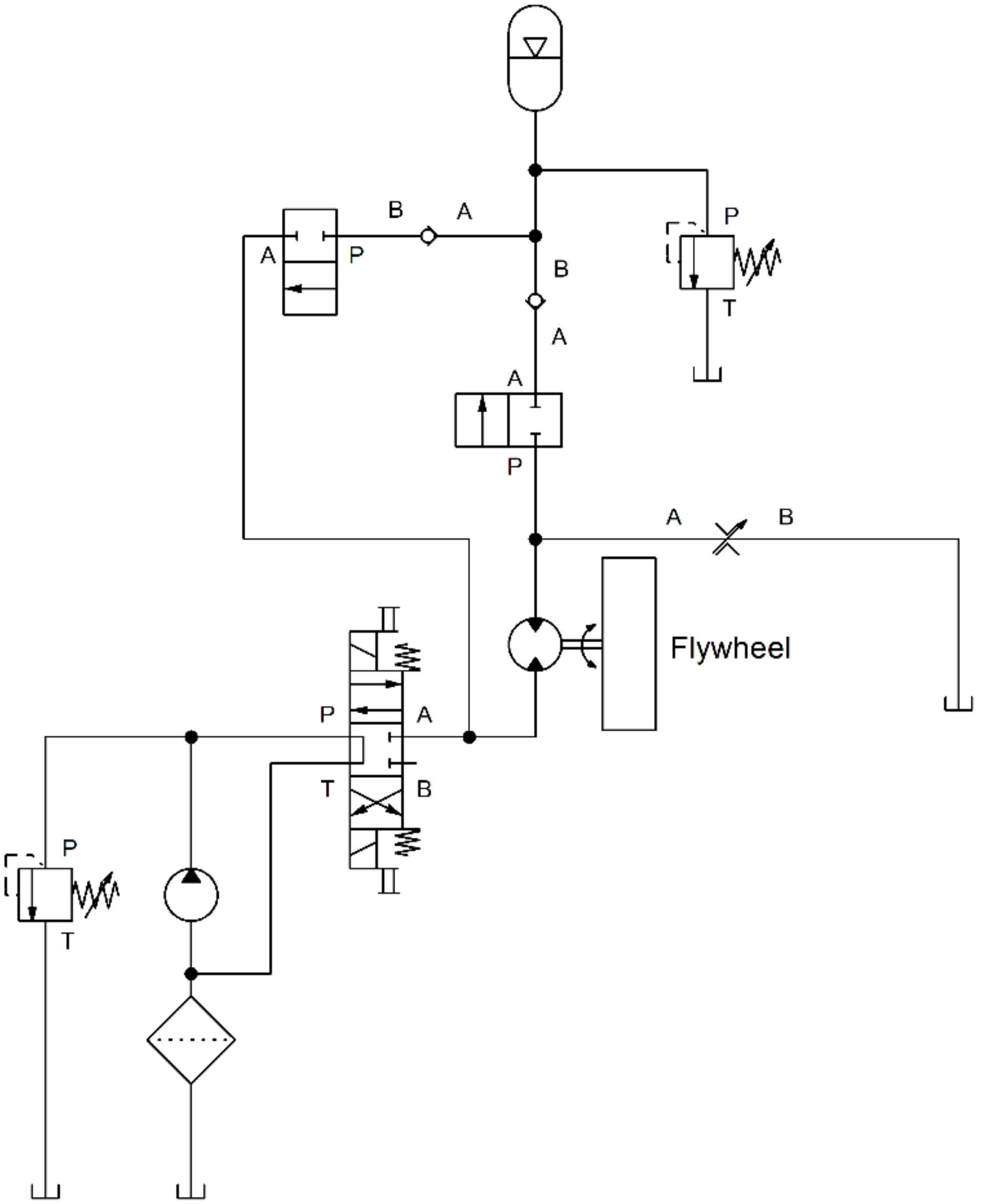

Figure 2. Hydraulic circuit

The second phase involved the physical implementation of the regenerative braking system. During this stage, the hydraulic circuit was assembled according to the approved design. Particular attention was given to the connection of mechanical, electrical, and hydraulic components, ensuring precise shaft alignment, proper integration of the flywheel, and the correct installation of inductive sensors for revolution counting. In parallel, a data acquisition system was implemented using an Arduino-based board, configured to record the flywheel's revolutions per minute (RPM) and pressure signals from the manometer connected to the circuit in real time. Leak tests were conducted to verify the absence of fluid leakage—an essential condition for maintaining operational pressure and ensuring the reliability of the experimental data.

Figure 1. Flywheel

Finally, the third phase corresponded to the validation and experimental analysis of the constructed system. A test protocol was developed, which included braking trials under different conditions: without accumulator load, and with progressive loads of 500 psi, 800 psi, and 1000 psi. For each condition, the deceleration time of the flywheel was recorded, and the corresponding rotational kinetic energy was calculated. The moment of inertia had been previously determined through modeling in SolidWorks. Numerical analysis of the recovered energy was performed by applying the trapezoidal rule to integrate the energy versus time data.

This experimental methodology enabled a comparative evaluation of the system's performance with and without the hydraulic accumulator under different load conditions, thus providing a quantitative assessment of the energy efficiency achieved. In addition, multiple repetitions of each trial were conducted to ensure the statistical consistency of the results, and corrective improvements were implemented in the system after identifying minor leaks during initial sealing tests.

4. Materials and methods

4.1. Prototype development

The development of the braking energy recovery system prototype was carried out through a meticulous process of design, construction, and experimental validation, aimed at ensuring its functionality and evaluating its energy performance.

The first step involved the construction of the hydraulic circuit, based on the previously developed design using specialized software. A three-phase electric motor connected to a 220V power source was used to drive a fixed-displacement hydraulic pump, which supplied pressurized fluid through a network of pipes and valves to a hydraulic motor and a bladder-type accumulator. The hydraulic pump converted the mechanical rotational energy from the electric motor into hydraulic energy, while the hydraulic motor operated in reverse, using fluid pressure to regenerate rotational motion.

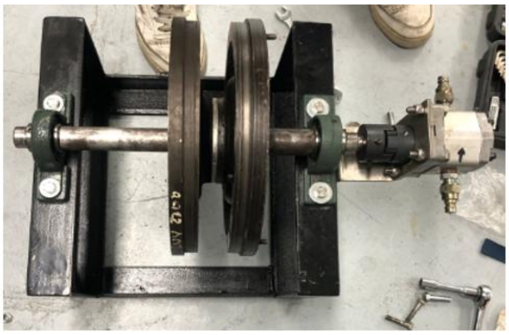

Figure 2. Prototype

The selected hydraulic accumulator, with a capacity of 0.75 liters and a pre-charge pressure of 150 psi, played a key role by storing hydraulic energy captured during the deceleration phase. This accumulator enabled the evaluation of the amount of energy stored and subsequently released within the system, which was fundamental for measuring the recovery efficiency.

In parallel with the hydraulic design, the mechanical components of the system were integrated. A high-strength steel shaft was coupled to the hydraulic motor, onto which two flywheels made of steel were mounted. These flywheels were designed to provide an appropriate moment of inertia for the prototype scale. The flywheels sustained rotational motion after the electric motor was switched off, thereby simulating the braking phase of a real vehicle. To ensure alignment and efficient torque transmission, self-aligning bearing blocks were used to support the shaft and minimize mechanical friction.

The construction of the prototype also included the implementation of an electronic instrumentation system for data acquisition. Inductive proximity sensors were strategically installed to detect the revolutions per minute (RPM) of the flywheels. These sensors were connected to an Arduino Uno microcontroller, which processed the pulse signals and transmitted the data to a computer for subsequent analysis. Additionally, an analog manometer was used to measure the hydraulic fluid pressure in real time, particularly at the inlet of the hydraulic motor.

During the assembly process, leak tests were performed on all hydraulic connections. These tests were essential to ensure that there were no leaks that could compromise the system’s efficiency. Minor leaks were initially detected and corrected at the accumulator and valve couplings, which were resolved by applying specialized sealants and reinforcing the mechanical fittings.

Upon completion of the construction, functional validation of the system was carried out. Initial no-load operation tests were performed to verify the behavior of the basic hydraulic circuit and ensure correct energy transfer between components. Subsequently, the accumulator was integrated into the circuit, allowing for observation of pressure variations and stored energy as a function of the simulated braking conditions.

4.2. Data acquisition

To quantitatively evaluate the efficiency of the braking energy recovery system, it was essential to implement a reliable data acquisition system capable of recording, in real time, the relevant kinematic and dynamic parameters of the prototype. Accurate measurement of variables such as angular velocity, braking time, and hydraulic pressure was critical for the subsequent analysis of recovered energy.

The adopted solution consisted of a low-cost acquisition platform based on the Arduino architecture, complemented by inductive sensors and analog pressure measurement devices. This approach was chosen due to its versatility, ease of integration, and responsiveness—essential requirements in an experimental setup of this nature. The core of the system was an Arduino Uno R3 board, specifically programmed to receive and process digital signals from a set of inductive proximity sensors. These sensors, strategically positioned near the flywheel’s rotational shaft, were configured to detect—non-invasively—each pass of a metallic element attached to the shaft, generating electrical pulses proportional to the system’s revolutions per minute (RPM).

Each detected pulse was interpreted as one full rotation of the flywheel, allowing for the accumulated count of revolutions and the determination of angular velocity over time. To improve the stability of the readings and avoid false counts due to signal bouncing, a debouncing algorithm was implemented within the Arduino IDE development environment.

In addition, an analog manometer was connected directly to the hydraulic circuit to measure the fluid’s dynamic pressure at the inlet of the hydraulic motor. Although this instrument was not electronically linked to the Arduino board, its visual reading complemented the data acquisition process by enabling the correlation of pressure variations with angular deceleration data.

The Arduino transmitted the captured data to a workstation via serial communication (USB), where a Python-based acquisition script was responsible for storing and processing the data in real time. This architecture allowed not only live visualization of RPM measurements but also the structured logging of data files for subsequent quantitative analysis.

4.3. Testing

In order to evaluate the performance of the braking energy recovery system, a structured experimental protocol was designed and executed to quantify energy efficiency under different hydraulic load conditions. The tests were conducted in a controlled laboratory environment, ensuring constant ambient temperature and the absence of external interference.

The experimental procedure began with the activation of the three-phase electric motor, which, through the hydraulic pump, delivered pressurized fluid to the hydraulic motor. This motor, in turn, transmitted rotational motion to a central shaft onto which two steel flywheels were mounted. Once the flywheels reached a stabilized angular velocity—measured in revolutions per minute (RPM) using the inductive sensors connected to the data acquisition system—the braking phase was initiated.

Braking consisted of cutting off the electrical supply to the motor, allowing the flywheel to decelerate solely under the action of the hydraulic system and its internal resistance. During this phase, the hydraulic fluid flow, driven by the motion of the hydraulic motor, enabled a portion of the rotational kinetic energy to be transferred to the hydraulic accumulator, where it was stored in the form of internal fluid pressure.

5. Results

Experimental tests of the regenerative braking system were conducted with a hydraulic accumulator charged at pressures of 500 psi, 800 psi, and 1000 psi. The system's kinetic energy was recorded throughout the braking process, both with and without the accumulator engaged, using a high-resolution data acquisition system. Data analysis involved calculating the area under the energy versus time curve using the trapezoidal numerical integration method, assuming a constant time interval of 0.33 seconds between measurements. This area represents the total energy dissipated or recovered during the braking process.

Table 1 summarizes the results obtained from the experimental tests evaluating the energy recovered during braking with and without the use of a hydraulic accumulator. The areas under the energy-time curves were calculated using numerical integration, and the relative reduction percentage represents the proportion of energy that was effectively stored rather than dissipated as heat. As shown, the use of the accumulator resulted in significant energy recovery across all tested pressures.

Table 1. Power comparison

Test Condition	Power without Accumulator (J·s)	Power with Accumulator (J·s)	Relative Reduction (%)
500 psi	1347.89	1142.52	15.24%
800 psi	2036.03	1742.25	14.43%
1000 psi	978.21	849.15	13.19%

It was observed that in all cases, the inclusion of the hydraulic accumulator enabled the recovery of a significant portion of the energy that would otherwise be entirely lost as heat in conventional braking. The energy recovery behavior revealed a clear trend: as the accumulator's pre-charge pressure increased, the relative recovery efficiency slightly decreased.

At 500 psi (see Figure 5), the system achieved an energy recovery of 15.24%, the highest among the tests. This suggests that at moderate pressures, the system can store regenerated energy more efficiently, with limited losses attributed to fluid friction, turbulence, and compressibility.

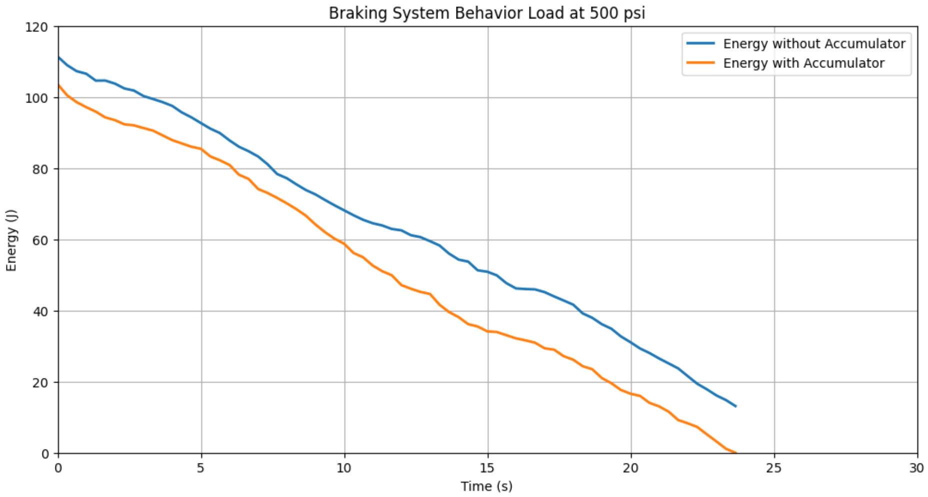

Figure 3. Energy comparison at 500 psi

At 800 psi, the recovery slightly decreased to 14.43%(see Figure 6). Although the storage capacity was greater, internal losses also increased, possibly due to the rise in flow resistance and internal heat generation within hydraulic components.

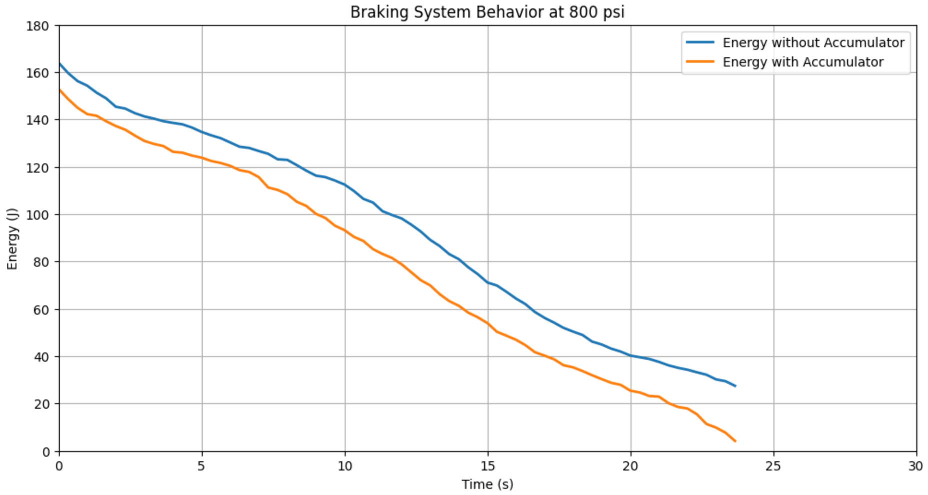

Figure 4. Energy comparison at 800 psi

Finally, at 1000 psi, the efficiency dropped to 13.19%(see Figure 7), indicating that although a higher charge pressure was available, the system experienced early saturation of the accumulator volume along with increased mechanical and thermal losses.

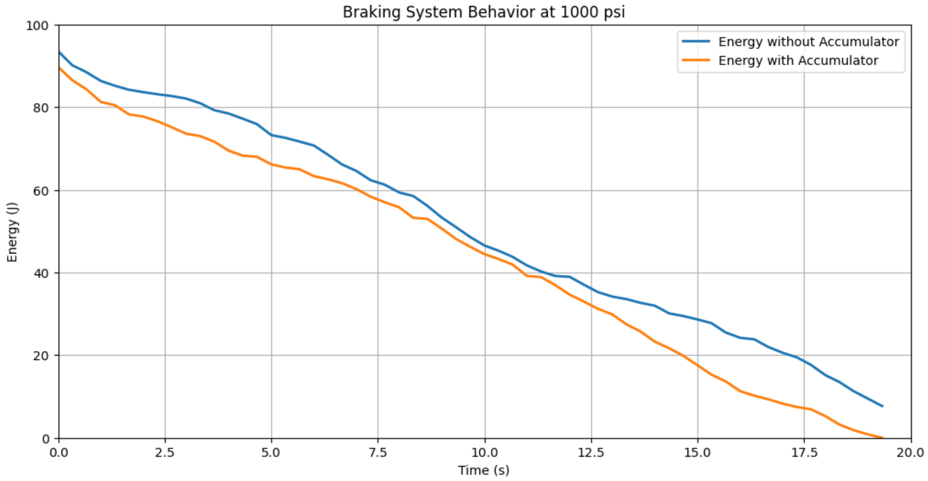

Figure 5. Energy comparison at 1000 psi

This behavior suggests the existence of an optimal operating point in terms of charge pressure to maximize energy recovery efficiency, while avoiding excessive pressures that may increase internal losses. The energy evolution during braking followed a continuously decreasing trend, demonstrating that the storage system progressively captures the available energy. The rate of energy decrease was steeper in the tests without the accumulator, reflecting rapid dissipation with no utilization of the kinetic energy.

In contrast, in the tests with the accumulator, the energy decreased more gradually, highlighting the damping effect of the hydraulic system on dynamic braking. Graphically, the energy curves with the accumulator remained at higher levels for longer periods compared to conventional braking, indicating effective energy storage.

6. Conclusions

The regenerative braking system using a hydraulic accumulator proved to be technically viable for the partial recovery of kinetic energy during the deceleration of a rotational system. Experimental results showed a consistent reduction in the area under the energy-time curve in the presence of the accumulator, with relative efficiencies reaching up to 15.24% at 500 psi, validating the principle of hydraulic energy storage for braking applications. Energy recovery efficiency slightly decreased as the accumulator's charge pressure increased, with relative reductions of 14.43% at 800 psi and 13.19% at 1000 psi. This behavior suggests that although higher pressures increase instantaneous storage capacity, they also lead to greater internal losses due to friction and fluid compressibility, negatively affecting overall system efficiency.

The analysis based on the area under energy versus time curves provided a comprehensive evaluation of the recovered energy, going beyond simple comparisons of initial and final values. This quantitative methodology is particularly useful for dynamically characterizing braking systems and validating the real effectiveness of energy recovery technologies.

The development and implementation of the data acquisition system within the test bench enabled high-fidelity recording of the system's energy evolution, which was essential for obtaining reliable results. This experimental approach can be replicated and adapted in future studies aimed at optimizing hydraulic accumulator configurations in industrial vehicles, heavy machinery, and other environments where electric regeneration is limited or unfeasible.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: M. A. Duran-Sarmiento: study conception and design; J. G. Ascanio-Villabona, N Y Castillo-León : data collection and experimental setup; M. A. Duran-Sarmiento, J. G. Ascanio-Villabona, B. E. Tarazona-Romero, A D Rincón-Quintero: analysis and interpretation of results; M. A. Duran-Sarmiento: draft preparation and final writing. All authors approved the final version of the manuscript.

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