Strategic Integration of Hydraulic Accumulators: Best Practices

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Hydraulic accumulators are indispensable in fluid power systems, providing critical functions such as energy storage, pressure holding or stabilization, and load balancing. However, their effectiveness heavily depends on correct application and circuit integration. This paper explores the principles guiding the proper use of hydraulic accumulators, emphasizing selection criteria, sizing, pre-charge pressure considerations, and safety protocols. It presents strategies for incorporating accumulators into hydraulic circuits to achieve specific functional objectives–such as energy storage, load levelling, and response enhancement–while utilizing the accumulator volume as much as possible and avoiding common pitfalls like exceeding pressure ratio, fluid compatibility issues and lifetime limitations. Through analytical modelling and application-based case studies, the paper illustrates how thoughtful accumulator integration can elevate system efficiency, reliability, and longevity. The findings aim to equip engineers with practical guidelines to make accumulators not just an add-on, but a performance enhancing element within their designs.

Keywords:
hydraulic accumulators, task, circuit integration, selection criteria, safety protocols, engineering guidelines

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1 Introduction

Hydraulic accumulators are indispensable components in modern fluid power systems, serving as energy storage devices that enhance system efficiency, stability, and responsiveness. Functionally analogous to electrical capacitors, accumulators store energy in the form of pressurized fluid, which can be released on demand to supplement pump flow, dampen pressure fluctuations, or provide emergency power in case of system failure [1]. Their integration into hydraulic circuits allows for improved dynamic performance, reduced energy consumption, and extended component lifespan, particularly in applications involving cyclic loads or transient pressure spikes.

The most prevalent type of accumulator in industrial and mobile applications is the gas-loaded or hydropneumatic accumulator, which utilizes a compressible gas—typically nitrogen—as a spring medium to exert pressure on the hydraulic fluid. The thermodynamic behavior of the gas, whether isothermal or adiabatic, significantly influences the accumulator's energy storage capacity and response characteristics [2]. Accurate modeling of this behavior is essential for optimizing accumulator performance, especially in high-frequency or high-pressure environments. Moreover, accumulators are increasingly being used in energy recovery systems, such as hydraulic hybrids and renewable energy platforms, where their ability to store and release energy efficiently plays a pivotal role in sustainable operation [3].

Given their multifaceted utility, hydraulic accumulators continue to evolve as critical elements in fluid-mechatronic systems. This paper presents hydraulic accumulators and verifies engineering practices for their use in the most common hydraulic applications. It outlines the fundamental operating principles of accumulator types such as bladder, piston, and diaphragm, and examines their roles in energy storage, pressure regulation, and shock absorption. Drawing from field-tested implementations and industry standards, the study highlights best practices for selection, sizing, and integration of accumulators into hydraulic circuits. Emphasis is placed on optimizing system reliability, improving energy efficiency, and extending component lifespan through proper accumulator usage. The findings serve as a practical reference for engineers and technicians seeking to enhance hydraulic system performance across mobile and industrial platforms.

2 Hydraulic accumulator types

Hydraulic accumulators are broadly categorized into two types based on their loading mechanism: mechanically loaded and gas loaded. Mechanically loaded accumulators use either springs or weights to exert pressure on the hydraulic fluid, while gas loaded accumulators rely on compressed gas — typically nitrogen — separated from the fluid by a bladder, diaphragm, or piston [1].

Spring-loaded accumulators operate by compressing a spring as fluid enters the chamber. This stored mechanical energy is released when the fluid is needed again. Their compact design and rapid response make them suitable for small-scale applications, but they suffer from a variable pressure output that depends on the spring's compression. Additionally, their limited stroke restricts fluid volume, making them unsuitable for high-pressure or large-volume systems. Weight-loaded accumulators, on the other hand, maintain constant pressure throughout the stroke by using a heavy mass to pressurize the fluid. While they offer excellent pressure stability and can handle large volumes, their size and weight make them impractical for mobile applications and require substantial structural support [1].

Table 1: Comparison of different accumulator types [1]

Group	Mechanically Loaded		Gas Loaded		
Type	Weight	Spring	Bladder	Diaphragm	Piston
Pressure	low	low	high	medium	high
Output Pressure	constant	linear	hyperbolic (isotherm) or steeper (polytropic/adiabatic)		
Friction Losses	yes	yes	no	no	yes
Energy Density	-	0	+	0	+
Storage Capacity	+	-	0	-	+
Placement	vertical	any	any	any	any
Response Time	slow	medium	fast	fast	medium

Gas loaded accumulators are more commonly used due to their versatility and efficiency. Bladder accumulators feature a flexible bladder that separates the gas from the fluid. They are lightweight, respond quickly, and are ideal for mobile hydraulic systems. However, they are limited to moderate pressure ranges and can degrade over time due to bladder fatigue or contamination. Diaphragm accumulators use an elastomeric diaphragm to separate the gas and fluid. They are well-suited for high-pressure applications and offer a simple, low-maintenance design, though their fluid capacity is generally lower than bladder types. Piston accumulators, which use a solid piston to separate the gas and fluid, are robust and capable of handling both high pressures and large volumes. They maintain consistent pressure and are highly durable, but they require regular maintenance and are more expensive to manufacture and install [1].

3 Hydraulic vs. electric energy storage

According to a comparative study published in Energies, the specific energy of a bladder hydraulic accumulator was found to be 9.4 times lower than that of an ultracapacitor under equivalent conditions. While this highlights the limitations of hydraulic systems in compact energy storage, it also underscores their advantages in power density and cost-effectiveness, especially for high-force, short-duration tasks [4].

Table 2: Comparison of energy and power density of different energy storage systems [4]

	Energy			Power		
Energy Storage System	Vol. $\frac{Wh}{m^3}$	Specific $\frac{Wh}{kg}$	Cost $\frac{US\$}{Wh}$	Vol. $\frac{kW}{m^3}$	Specific $\frac{kW}{kg}$	Cost $\frac{US\$}{kW}$
$LiFePO_4$ Battery	**195144**	**115.2**	**0.45**	325.24	0.192	270.83
Ultracapacitor	2539.7	2.72	138.67	2588	2.21	217
Bladder Accumulator	1227	0.29	404.68	**7548**	**2.69**	**75**

4 Basic Accumulator Calculations

Brief accumulator calculations are also presented for user reference. Such calculations include calculation of precharge pressure and available volumes at different pressures for different use cases. The following variables will be used in calculations:

p_0 ... gas precharge pressure [bar]

p_1 ... min working pressure [bar]

p_2 ... max working pressure [bar]
V_0 ... effective gas volume (accumulator volume incl. gas bottles) [l]
V_1 ... gas volume at p_1 [l]
V_2 ... gas volume at p_2 [l]
T_0 ... gas precharge temperature (normally 20°C) [°C]
T_{min} ... min working temperature of the gas [°C]
T_{max} ... max working temperature of the gas [°C]
n_c ... polytropic index for charging accumulator [-]
n_d ... polytropic index for discharging accumulator [-]

4.1 Gas working temperatures

Estimating working gas temperatures is challenging. The minimum is usually the lowest ambient temperature, while the maximum falls between the highest ambient and fluid temperatures. Factors influencing the maximum include accumulator function, type, ambient and fluid temperatures, and fluid exchange volume. In accumulators where gas is mostly in contact with fresh fluid (such as bladder types), or in pump support roles with high fluid exchange and hot oil, fluid temperature has greater influence than ambient air.

Fluid temperature should be factored into shock absorption and pulsation dampening, but volume exchange remains minimal in these two applications. The maximum working gas temperature can therefore typically be estimated by averaging the highest fluid and ambient temperatures.

For energy storage applications in which pumps operate solely to charge the accumulator, the maximum anticipated ambient temperature may be used. This is because accumulators are filled with oil at ambient temperature, and the gas temperature remains nearly equivalent to the ambient temperature.

4.2 Precharge pressure

Typically, precharge pressure is set to about 90 % of the system's minimum operating pressure (for energy storage), striking a balance that allows fluid to enter the accumulator without compromising its ability to discharge when needed. Setting the precharge too high prevents fluid from entering the accumulator, while setting it too low risks bottoming out the gas chamber, reducing the accumulator's lifespan and effectiveness. Proper selection of precharge pressure is essential for maintaining pressure stability and ensuring reliable hydraulic performance. Care must be taken, that the ratio between maximum pressure and precharge pressure doesn't exceed accumulators' compression ratio. Typical compression ratio for bladder accumulators is 4, while diaphragm accumulators can go up to 8.

Recommended precharge pressure:

- Energy storage and pump support: 90 % of minimum working pressure
- Shock adsorption: 60 % to90 % of average working pressure
- Pulsation damping: 60 % of average working pressure

Precharge pressure is always calculated for maximum working gas temperature (see previous chapter). If we take an example for energy storage, we can calculate precharge pressure at maximum temperature with (1) and then convert to precharge pressure at 20 °C with isochoric relation for ideal gas (2). [5]

$$p_{0@T_{max}} = 0{,}9 \cdot p_1 \tag{1}$$

$$p_0 = p_{0@T_{max}} \frac{T_0 + 273}{T_{max} + 273} \tag{2}$$

4.3 Calculation of available fluid volume in accumulator

A key parameter in energy storage is the amount of hydraulic medium stored in the accumulator. This can be calculated by combining the general gas equations for polytropic compression (3) - charging and decompression (4) - discharging, resulting in equation (5) [6].

$$p_0 V_0^{n_c} = p_2 V_2^{n_c} \tag{3}$$

$$p_2 V_2^{n_d} = p_1 V_1^{n_d} \tag{4}$$

$$\Delta V = V_1 - V_2 = V_0 \cdot \left(\frac{p_0}{p_2}\right)^{\frac{1}{n_c}} \cdot \left(\left(\frac{p_2}{p_1}\right)^{\frac{1}{n_d}} - 1\right) \tag{5}$$

Polytropic index values reflect how heat transferred during compression/expansion [7]:

- isothermal (slow > 3 min, with full heat exchange) $n = 1$
- adiabatic (fast < 1 min, with no heat exchange) $n = \kappa = 1{,}4$ (for diatomic gases)
- polytropic (partial heat exchange) $1 < n < \kappa$

Examples of different processes:

- accumulation of energy (pump support): adiabatic charge and discharge
- emergency, safety functions: isothermal charge and adiabatic discharge
- leakage and volume compensation: isothermal charge and discharge

Some calculators add additional correction factor to the results [8].

4.4 Calculating required accumulator size for pulsation dampening

The use of accumulators as pulsation dampeners is particularly suitable for constant pressure systems, since their effectiveness diminishes below and does not perform optimally at pressures significantly above the operating pressure. Nevertheless, in hydraulic applications, the necessary volumes for effective pulsation dampening are relatively small (typically within the deciliter range). Consequently, it is possible to cover a broad pressure range by utilizing high compression ratio diaphragm accumulators, precharged to comparatively low precharge pressures.

To determine the required accumulator size for a piston pump, it is necessary to identify its operating pressure p and define maximum allowed pulsation α [%]. The fluctuating fluid volume produced by the pump, which the accumulator must absorb can be calculated out of the piston volume V_p [l] and the pump type coefficient K [-] [8]. Since the process is adiabatic, a value of 1,4 is used for n. If the recommended precharge pressure of 0,6 is applied for pulsation dampening, the equation can be further simplified to (6):

$$V_0 = \frac{K \cdot V_p}{\left(\frac{p_0}{p_1}\right)^{\frac{1}{n}} - \left(\frac{p_0}{p_2}\right)^{\frac{1}{n}}} = \frac{K \cdot V_p}{\left(\frac{p_0}{p \cdot (1-\alpha)}\right)^{\frac{1}{n}} - \left(\frac{p_0}{p \cdot (1+\alpha)}\right)^{\frac{1}{n}}} = \frac{K \cdot V_p}{\left(\frac{0,6}{(1-\alpha)}\right)^{\frac{1}{1,4}} - \left(\frac{0,6}{(1+\alpha)}\right)^{\frac{1}{1,4}}} \quad (6)$$

For pulsation dampening it is crucial that the accumulator is mounted close to the pump and that the flow is directed to the accumulator using a T-piece as shown in Figure 1, where use a special T-piece (shown on the left) is shown in the middle and use of a normal T-piece is shown on the right.

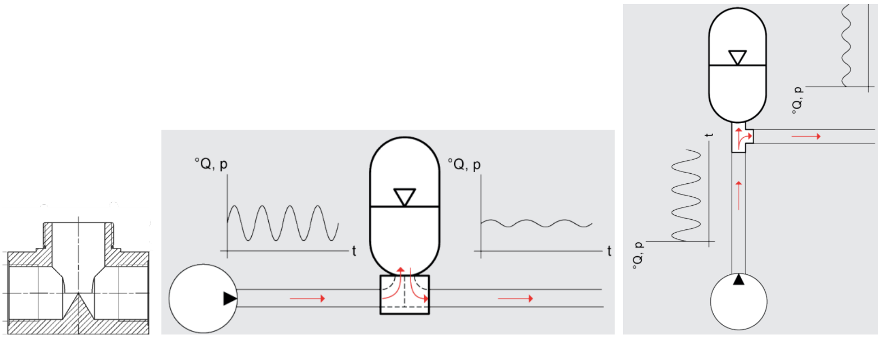

Figure 1: Mounting of accumulators for pulsation dampening
Source: [8], [9]

4.5 Calculating required accumulator size for shock adsorption

Shock adsorption is required when high flow in long pipelines is suddenly stopped, such as when a hydraulic valve closes quickly. The fluid's inertia creates a pressure surge that must be absorbed by converting its kinetic energy into gas (adiabatic compression). Therefore, the equation (7) applies [10]. In this case p_1 represents pressure in fluid line before closing a valve and p_2 is the maximum allowable line pressure during the shock

$$\frac{mv^2}{2} = -\int p\mathrm{d}V = -\frac{p_2V_2 - p_1V_1}{1-n} \text{(adiabatic compression)} \quad (7)$$

If we combine this with first isothermal compression from $V_0 p_0$ to $V_1 p_1$ and then adiabatic compression from $V_1 p_1$ to $V_2 p_2$ and solve for effective gas volume V_0 we get (8).

$$V_0 = \frac{mv^2 \cdot (1-n)}{2 \cdot p_0 \cdot 10^5 \cdot \left(\left(\frac{p_2}{p_1} \right)^{1-\frac{1}{n}} - 1 \right)} \tag{8}$$

Mass m [kg] of the fluid can be calculated out of fluid density ρ [$\frac{\text{kg}}{\text{m}^3}$], pipe length l [m] and pipe diameter d [mm]. Fluid velocity can be calculated out of flow Q [$\frac{\text{l}}{\text{min}}$] and pipe diameter. Considering non-SI conversions we get equation (9).

$$V_0 = \frac{\rho \cdot l \cdot Q^2 \cdot (1-n)}{1{,}8 \cdot 10^8 \cdot \pi \cdot d^2 \cdot p_0 \cdot \left(\left(\frac{p_2}{p_1} \right)^{1-\frac{1}{n}} - 1 \right)} \tag{9}$$

As with pulsation dampening, the required volumes for shock absorption in hydraulic systems typically fall within the deciliter range, making diaphragm accumulators particularly suitable for these applications. Conversely, in water supply systems and hydropower plants - where pipelines are extensive and diameters substantial - the accumulator stations needed for shock absorption generally require capacities in the range of 1000 liters.

4.6 Other Caveats when Choosing Hydraulic Accumulators

- **Hydraulic medium compatibility:** Accumulator elastomers (bladder/diaphragm/seals) and accumulator shell have to be compatible with the hydraulic medium.
- **Temperature compatibility:** Accumulator elastomers and shell have to withstand highest and lowest operating temperatures.
- **Max compression ratio:** must not be exceeded $\left(\frac{p_2}{p_0}\right)$
- **Certificate:** Correct certificate for destination country / place of installation has to be chosen:
  - PED – Europe
  - ASME – America
  - DNV, BV, … - ships
  - EAC – Russia
  - ML – China
  - …

- **Gas valve adapter:** Correct gas valve adapter for destination country has to be chosen.
- **Lifetime:** If pressure is in a certain range, it has “infinite” cycle life of 2M cycles, when outside of this range, cycle number could be as low as few thousand. This parameter has to be requested from the manufacturer and should be on the PED certificate of the accumulator.

5 Practical applications of hydraulic accumulators

Before digging into practical examples, we must be familiar with the correct protection of hydraulic accumulators, as outlined in **EN 14359**. This standard emphasizes the importance of integrating appropriate safety mechanisms (safety pressure relief valves, gas safety valves, and burst discs) to prevent overpressure, gas leakage, and structural failure. These protective measures must be tailored to the operating conditions of the hydraulic accumulator, ensuring compliance with the **Pressure Equipment Directive (PED) 2014/68/EU**. Once properly safeguarded, hydraulic accumulators can be confidently deployed across a wide range of applications [11].

5.1 Safe use of hydraulic accumulators

How to properly protect the hydraulic accumulators is described in EN 14359 with circuit examples in Annex C [11] and summarized in [12]. Hydraulic accumulators which will be used in Europe require a PED certificate when they meet specific criteria related to pressure and volume. The key threshold is when the product of pressure and volume exceeds 50 bar·liters, and when the accumulator volume is greater than 1 liter—both conditions apply to fluid group 2, which includes mineral oil and nitrogen. In rare cases, even piping on the gas side may fall under PED if it exceeds certain dimensions and pressure combinations (e.g., DN > 32 mm and P × DN > 1000 bar·mm). It is similar with ASME, but there is no minimum pressure limit defined.

When an accumulator falls under PED/ASME:

- It must be purchased with a valid PED/ASME certificate.
- It must be protected according to EN 14359, including:

- a manual isolation valve,
- a ball valve to drain back to tank,
- a dedicated PED/ASME certified safety pressure relief valve (not shared with the main system), and
- a non-isolatable pressure gauge for monitoring accumulator pressure.

For systems with multiple accumulators in parallel, shared protection components may be used, provided the configuration still meets PED/ASME safety requirements.

Certified safety pressure relief valve must be correctly dimensioned, to ensure safe operation. It has to handle entire flow that could be causing the pressure rise (typically flow of all the pumps connected to the accumulator; attention has to be paid to external forces acting on cylinders/hydromotors as well), so that maximum allowable pressure of the accumulator is not exceeded by more than 10 % taking back pressure in the tank line into account.

When an accumulator doesn't fall under PED or ASME, sound engineering practices must be used to protect it, therefore following EN 14359 is always recommended at least with pressure gauge and non-certified pressure relief valve.

5.2 Practical Examples of Safety Equipment Configuration

This chapter outlines typical protection methods following EN 14359, detailed in annex C [11]. The most common is a safety block (Figure 2), which combines an isolation valve, discharge valve, and safety pressure relief valve, with ports for the hydraulic system, accumulator, tank, and pressure gauge. Use of individual components is also permitted. The pressure gauge must connect directly to the accumulator (without isolation device) or via quick coupling; otherwise, a gauge check port should be included to ensure proper function. A check valve on the pump side is advised to guard against pressure release towards the pump (during pump maintenance or when changing the pressure filter).

When using multiple accumulators each individual accumulator can have its own safety block. But there is an exception that allows using only one safety pressure relief valve for all accumulators (Figure 3), while still allowing individual isolation and discharge of each accumulator, easing maintenance on the system. Care must be taken that fully charged accumulators don't remain isolated for too long, as ambient temperature rise may increase gas pressure, exceeding max pressure of the accumulator. This can be avoided using burst discs on the gas side.

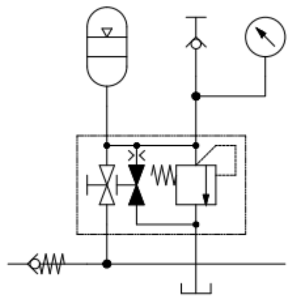

Figure 2: Protecting single accumulator using accumulator safety block
Source: [own work]

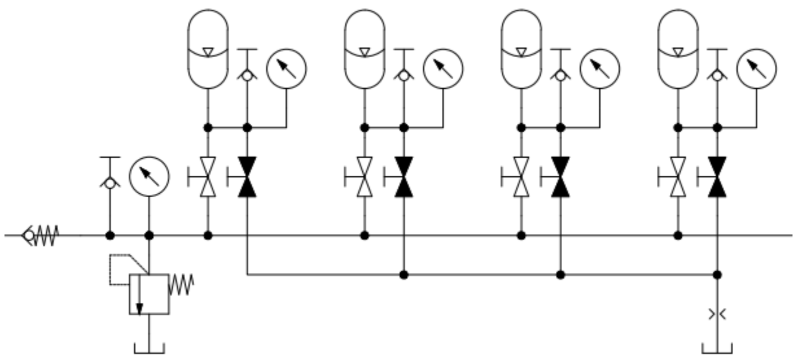

Figure 3: Protecting multiple accumulators using individual components [own work]
Source: [own work]

5.3 Practical example of using hydraulic accumulators for safe operation of a Pelton hydraulic power plant

The Pelton turbine (Figure 4) typically features three primary actuators requiring control: a jet deflector, which redirects the jet away from the turbine; a main inlet or shut-off valve, utilized to halt water flow through the turbine; and needle adjustment cylinders, designed to accurately regulate the flow through each individual nozzles [13].

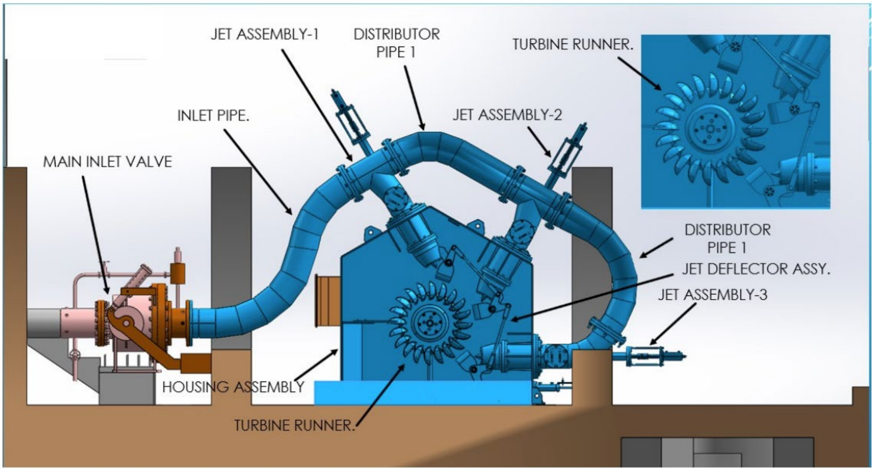

Figure 4: Pelton turbine with three nozzles
Source: [13]

During power plant operation, the hydraulic unit is responsible for adjusting the nozzle needles and jet deflector to ensure the generator output matches grid power demand. The hydraulic power unit (HPU) supplies actuators via the accumulator; when accumulator pressure decreases, the hydraulic pump replenishes it. It is essential to ensure that the pump does not start excessively frequently and that the accumulator is refilled within an appropriate period.

In emergency situations, such as when the hydraulic pump fails to start as anticipated, the generator should be shut down promptly. The jet deflector must retract to redirect the jets away from the turbine, and all nozzles need to be closed. Therefore, sufficient pressurized fluid should be stored in the accumulator to stop the turbine safely. The cylinder sizes, closing times and minimum required pressures are different for different turbine sizes.

Accumulator design steps:

- Calculate cylinder volumes and emergency directions.
- Calculate volumes needed for normal operation and emergency.
- Adjust accumulator volume, emergency, pump turn on, and pump turn off pressures while iterating equation (5) which calculates available fluid volume in

normal operation (Figure 5) and emergency operation (Figure 6) and compare it to available volume in accumulator.

– Define required pump size and motor power based on charging time of the hydraulic accumulator.

		system pressure when pump turns off		psys=	230 bar
		system pressure when pump turns on		pmin=	120 bar
cylinder	qty	larger side of cylinder volume		number of strokes	needed volume
Jet deflector	1		0,16 l	1,5	0,24 l
Shut-off valve	1		0,53 l	0	0,00 l
Needle adjustment 1	1		0,31 l	1	0,31 l
Needle adjustment 2	1		0,31 l	1	0,31 l
SUM	4		1,32 l		0,86 l
accumulator	qty	rated volume	precharge pressure	worst case total working volume max	min
main accumulator	1	10,0 l	45 bar	1,28 l	1,13 l
SUM	1	10,0 l		1,28 l	1,13 l
pump		flow rate		accumulator charge time max	min
pump flow rate		10,9 l/min		7 s	6 s

Figure 5: HPU Calculation – Normal Operation Evaluation

Source: [own work].

		system pressure when emergency stop procedure starts		p_{em}=	110 bar
		system pressure when emergency stop procedure ends		p_{emmin}=	50 bar
cylinder	qty	direction	full stroke emergency volume	safety factor / sicherheitsfactor	needed volume
Jet deflector	1	Retraction	0,11 l	1,5	0,16 l
Shut-off valve	1	Gravity	0,00 l	0	0,00 l
Needle adjustment 1	1	Extension	0,31 l	1,5	0,47 l
Needle adjustment 2	1	Extension	0,31 l	1,5	0,47 l
SUM	4		0,74 l		1,10 l
accumulator	qty	rated volume	precharge pressure		WC total avail. volume
main accumulator	1	10,0 l	45 bar		2,75 l
SUM	1	10,0 l			2,75 l

Figure 6: HPU Calculation – Emergency Stop Evaluation

Source: [own work]

Each HPU is tested after assembly where volumes are measured. Comparison of results is presented in Table 3. Please note that the calculations shown above are for minimum ambient temperature (0 °C), but they were made also for 20 °C making them comparable to measurements which were made at ca. 20 °C.

Table 3: Comparison of different accumulator types

	Calculation 0°C	Calculation 20°C	Measurement ~20°C
Recharge Time ($p_{min} \rightarrow p_{max}$)	7 s	8 s	11 s
Available Volume ($p_{max} \rightarrow p_{min}$)	1.13 l	1.28 l	1.37 l
Available Volume ($p_{em} \rightarrow p_{emmin}$)	2.75 l	3.11 l	3.22 l

The HPU was already commissioned in Guyana at a 0,8 MW power plant (water flow 200 l/s with 207 m head; 488 mm turbine runner diameter).

6 Conclusion

Hydraulic accumulators become safe dynamic enhancers of system performance, when strategically integrated. This paper has outlined the critical parameters—selection, sizing, and safety measures—that govern their effective use. By applying thermodynamic principles and engineering calculations, designers can tailor accumulator configurations to meet specific functional goals such as energy storage, pulsation dampening, and shock absorption. Moreover, adherence to safety standards like EN 14359 and PED ensure not only regulatory compliance but also operational reliability. Through practical examples, including the Pelton turbine application, it becomes evident that accumulators are not merely auxiliary devices but essential contributors to system resilience and efficiency.

Engineers who embrace these best practices will unlock the full potential of hydraulic accumulators, driving reliability across fluid power systems.

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