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By: Wesley Bylsma



SPREADSHEET ACCUMULATOR SIZING FOR HYBRID HYDRAULIC APPLICATIONS USING THE BENEDICT-WEBB- RUBIN EQUATION OF STATE

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ABSTRACT

A simple and effective method using optimization with the Benedict-Webb-Rubin equation of state is presented to size accumulator volumes in hybrid hydraulic applications given the pre-charge, minimum and maximum operating pressures.

1.0 INTRODUCTION

In the automotive industry recent efforts have focused on ways to drive down operating costs by reducing fuel consumption requirements. The development of hybrid vehicles—electric and hybrid, and more recently fuel cells are examples of this interest. The main component of this approach is an energy storage device such as a capacitor for electric or an accumulator for hydraulic applications. The main operating principal is the assumption that the duty cycle of the system will consist of periods when 1) the system power demand is low, at which time excess energy can be stored, and 2) the system power demand is high, at which time the stored energy can be used to supplement the power demand. Reference to these periods is more commonly referred to as regenerative braking or power assist. An outline of the remainder of this report is as follows: Section 2 presents the principals behind the operation of an accumulator. Section 3 covers the factors affecting the size. Section 4 discusses the calculations to define the size. Section 5 gives an example of a spreadsheet solution. Section 6 gives a summary and conclusion

2.0 PRINCIPALS OF OPERATION

The focus of this report is on energy storage sizing for the hybrid hydraulic solution. For this application accumulators are used as energy storage devices. These accumulators are based on the principle that gas is compressible and oil is incompressible. Oil flow into the accumulator compresses the gas by reducing its

storage volume. Energy is stored by the volume of hydraulic fluid that compressed the gas under pressure. If the fluid is released will quickly flow out under the pressure of the expanding gas. This will also require a reservoir to store the fluid that has exited the accumulator or before it is pumped in.

Some common types of accumulators are depicted in Figure 1. The main difference between them is in how the gas is confined to a specific volume.

The rate at which compression and expansion of the gas takes place affects the gas state—which is defined by pressure, volume, and temperature. Slow rates are known as isothermal processes—the rate is so slow that the temperature of the gas is essentially constant. Fast rates are known as adiabatic processes—the rate is so fast that the temperature of the gas changes but not the surroundings (no gain or loss of heat). The relationship between pressure and volume is affected by these processes. Appendix A contains more specifics on these processes with correction factors for ideal gases. It is evident, however, that the temperature must be accounted for.

Fig. 1 Typical bladder, diaphragm and piston accumulators

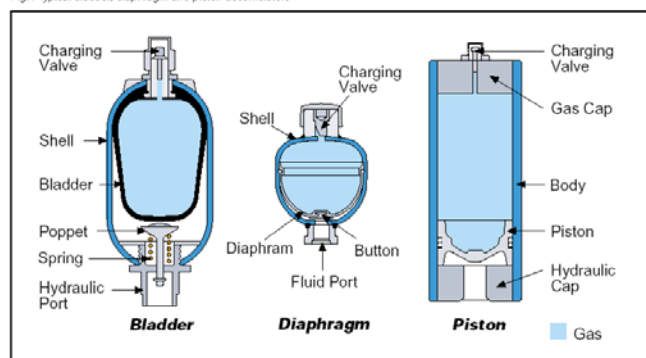


Figure 1 – Types of accumulators (Source: Parker Hannifin, Hydraulic Accumulator Division)

3.0 ACCUMULATOR SIZING

Sizing is based on the gas charge of the accumulator. The change in volume and pressure determines how much fluid can be stored and released. To start the sizing process we begin with some defined quantities:

p_0 - pre-charge at room temperature with-no fluid

p_1 - minimum operating pressure

p_2 - maximum operating pressure

V_0 - pre-charge volume

V_1 - minimum pressure volume

V_2 - maximum pressure volume

$\Delta V = V_1 - V_2$ - charge volume

The pre-charge state plays a key role in sizing the accumulator. Common "Rules of Thumb" are:

$$p_0 \approx 0.9 p_1$$

to reduce bladder wear on the inlet valve,

$$p_2 \leq 4 p_0$$

for consideration of bladder elasticity performance (see Appendix A). From these conditions the pre-charge volume can be approximated from

$$V_0 \approx 1.5 \dots 3 \times \Delta V.$$

The reservoir is roughly three times the accumulator pre-charge volume to provide a low-pressure chamber.

4.0 CALCULATION

We diverge here from the procedure outlined in Appendix A for a more accurate approach for temperature considerations. Departing from the ideal gas relationship

$$PV = mRT$$

we use the Benedict-Webb-Rubin (BWR) Equation of State ($p - v - T$) defined as

$$p = \frac{RT}{v} + \frac{\left(B_0 RT - A_0 - \frac{C_0}{T^2}\right)}{v^2} + \frac{(bRT - a)}{v^3} + \frac{a\alpha}{v^6} + \frac{c\left(1 + \frac{\gamma}{v^2}\right)e^{\frac{-\gamma}{v^2}}}{v^3 T^2}$$

Here eight experimental constants are used, with good prediction results up to about $\rho \leq 2.5 \rho_{cr}$, where ρ_{cr} is the density of the substance at the critical point. See [4].

The gas is assumed to be nitrogen, which has well documented properties and whose coefficients for the BWR equation are shown in Figure 2.

From the initial (pre-charge) pressure and accumulator volume the mass of the gas can be determined. Using the mass of the gas the minimum and maximum accumulator volume can be determined from the minimum and maximum pressures required and operating temperature at these points. The non-linearity of the BWR makes these determinations difficult and requires an iterative method.

$$\begin{aligned} a &= 0.025102 \left(\frac{l}{g-mol} \right)^3 atm \\ A_0 &= 1.053642 \left(\frac{l}{g-mol} \right)^2 atm \\ b &= 0.0023277 \left(\frac{l}{g-mol} \right)^2 \\ B_0 &= 0.0407426 \left(\frac{l}{g-mol} \right) \\ c &= 728.41 \left(\frac{l}{g-mol} \right)^3 (K)^2 atm \\ C_0 &= 8059.00 \left(\frac{l}{g-mol} \right)^2 (K)^2 atm \\ \alpha &= 0.0001272 \left(\frac{l}{g-mol} \right)^3 \\ \gamma &= 0.005300 \left(\frac{l}{g-mol} \right)^2 \\ R &= 0.0820544 \left(\frac{l}{g-mol} \right) \frac{atm}{K} \end{aligned}$$

Figure 2 – BWR constants (Nitrogen)

An easy solution, however, is to use an optimization method. This technique requires a cost function to minimize. The cost function can be defined as

$$e = (p_{desired} - p_{BWR})^2$$

where p_{BWR} (the BWR equation) is a function of variables m , V and T . The following procedure outlines the steps to determine the mass of the gas, and the minimum and maximum volumes required.

- 1) to find the initial mass of the gas set $p_{desired} = p_0$ and $p_{BWR} = p_{BWR}(m)$ then optimize the cost function e

over the mass m . Note that this is really an optimization over the molar specific volume since

$$v = \frac{V_0}{m} M \left(\frac{l}{k - mol} \right)$$

where the molar mass (for nitrogen) is

$$M = 28.013 \left(\frac{kg}{k - mol} \right)$$

and the gas constant (for nitrogen) is

$$R = \frac{R_u}{M} = 0.2967 \left(\frac{kJ}{kg K} \right)$$

with a universal gas constant of

$$R_u = 8.314 \left(\frac{kJ}{k - mol K} \right)$$

2) to find the minimum volume, using the mass of the gas from step 1, set $p_{desired} = p_1$ and $p_{BWR} = p_{BWR}(V_1)$ then optimize the cost function e over the volume V_1 . Note that

$$v_1 = \frac{V_1}{m} M \left(\frac{l}{k - mol} \right)$$

3) to find the maximum volume, using the mass of the gas from step 1, set $p_{desired} = p_2$ and $p_{BWR} = p_{BWR}(V_2)$ then optimize the cost function e over the volume V_2 .

An example of this process is provided in the next section using a spreadsheet (Microsoft Excel).

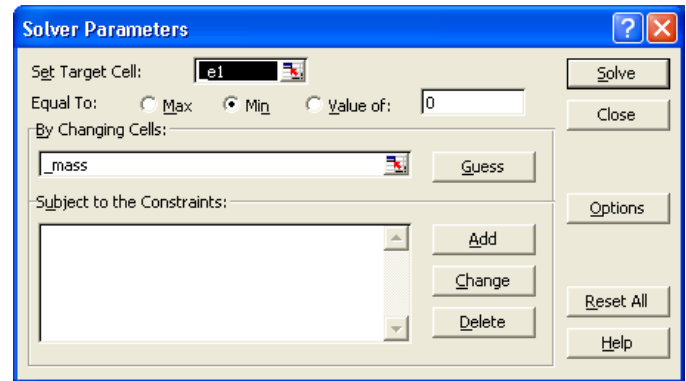


Figure 3 – Microsoft Excel Solver Dialog Screen

5.0 SPREADSHEET EXAMPLE

Figure 3 shows the dialog window of the solver used to perform the optimization process. The solver can be started from the “Tools” menu from within Microsoft Excel. The solver is an “Add-In”, so be sure it has been loaded before trying to use it. For the optimization method we quote directly from the Excel help text:

“Microsoft Excel Solver uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Waren, Cleveland State University.

Linear and integer problems use the simplex method with bounds on the variables, and the branch-and-bound method, implemented by John Watson and Dan Fylstra, Frontline Systems, Inc. For more information on the internal solution process used by Solver, contact: Frontline Systems, Inc., P.O. Box 4288, Incline Village, NV 89450-4288, (702) 831-0300, Web site: <http://www.frontsys.com>”

As shown in Figure 3, the Target Cell is the cost or error function (names have been defined for cell ranges such as $e1$, $_{mass}$, $_{volume}$, etc.). The Changing Cells are the variables to change that affect the Target Cell. The solver will be used on the spreadsheet discussed next.

Figures 4-7 show an example spreadsheet setup to do the calculations discussed in Section 3. The first column contains the variable names. The second column contains the variable values. The third column contains the variable units. The fourth column (near bottom) contains the cost functions. Each cost function is used to get m from the V_0 , p_0 and T , to get V_1 from p_1 , T , and m , and to get V_2 from p_2 , T , and m , respectively. Notice the outlined boxes---values for V , m , and T are entered here. The orange boxes are the pressure calculated in different units from the BWR equation based on the values for volume, mass, and temperature above.

Nitrogen				
a	0.025102	(l/g-mol) ³ atm		
A0	1.053642	(l/g-mol) ² atm		
b	0.002328	(l/g-mol) ²		
B0				
c				
CO	8059.000	(l/g-mol) ² (K) ² atm		
alpha	0.000127	(l/g-mol) ³		
gamma	0.005300	(l/g-mol) ²		
R	0.082054	(l/g-mol)atm/(K)		
volume	80.00	liters		
mass	11.84	kg		
spec. vol	0.006758	m ³ /kg		
vmol	0.189319	m ³ /kmol		
T	302.00	K		
	28.85	C		
	109.53	F		
P	133.23	atm		
	13500.00	Pa		
	135.00	bar		
	1958.00	psi		
=8.134kJ/(kmol K) / 101.325 kPa				
	volume	P(bar)	error	mass
PreCharge	80.00	135	0.00	11.84
Min	80.00	150	225.00	0.006758
Max	80.00	350	46225.00	0.006758
dV	0.00			
Rmax.				
Rmin.				

Figure 4 – Spreadsheet Example a

The green boxes denote values that are found through the optimization process. All optimization processes are done using the outlined boxes and the cost (error) functions. The steps below outline the procedure to follow. Steps 1-3 refer to Figure 4.

Step 1

Set the initial temperature and volume to their pre-charge values. Copy the value of the volume into the volume box for the pre-charge volume (lower bottom). This is used for later calculations. Set the initial pressures.

Step 2

Run the solver to minimize the pre-charge pressure error by changing the mass. The error should go to zero.

Step 3

The pre-charge mass of the gas at the pre-charge pressure is now known. (11.84).

Steps 4-5 refer to Figure 5.

Nitrogen				
a	0.025102	(l/g-mol) ³ atm		
A0	1.053642	(l/g-mol) ² atm		
b	0.002328	(l/g-mol) ²		
B0	0.040743	(l/g-mol)		
c	728.410	(l/g-mol) ³ (K) ² atm		
CO	8059.000	(l/g-mol) ² (K) ² atm		
alpha	0.000127	(l/g-mol) ³		
gamma	0.005300	(l/g-mol) ²		
R	0.082054	(l/g-mol)atm/(K)		
volume	72.51	liters		
mass	11.84	kg		
spec. vol	0.006126	m ³ /kg		
vmol	0.171605	m ³ /kmol		
T	302.00	K		
	28.85	C		
	109.53	F		
P	148.04	atm		
	15000.00	Pa		
	150.00	bar		
	2175.55	psi		
=8.134kJ/(kmol K) / 101.325 kPa				
	volume	P(bar)	error	mass
PreCharge	80.00	135	225.00	11.84
Min	72.51	150	0.00	0.006126
Max	80.00	350	40000.00	0.006758
dV	7.49			
Rmax.	240.00			
Rmin.	232.51			

Figure 5 – Spreadsheet Example b

Step 4

Leaving the mass value as it is, run the solver to minimize the minimum pressure error by changing the volume. The error should go to zero.

Step 5

The minimum accumulator volume of the gas at the minimum pressure is now known. (72.51). Copy the value of the volume down to the minimum volume green box (lower bottom).

Steps 6-7 refer to Figure 6.

Step 6

Leaving the mass value as it is, run the solver to minimize the maximum pressure error by changing the volume. The error should go to zero.

Step 7

The maximum accumulator volume of the gas at the maximum pressure is now known. (35.93). Copy the value of the volume down to the maximum volume green box (lower bottom).

Nitrogen				
a	0.025102	(l/g-mol)*3atm		
A0	1.053642	(l/g-mol)*2atm		
b	0.002328	(l/g-mol)*2		
B0	0.040743	(l/g-mol)		
c	728.410	(l/g-mol)*3(K)^2atm		
C0	8059.000	(l/g-mol)*2(K)^2atm		
alpha	0.000127	(l/g-mol)*3		
gamma	0.005300	(l/g-mol)		
R	0.082054	(l/g-mol)		
volume	35.93	liters		
mass	11.84	kg		
spec. vol	0.003035	m^3/kg		
vmol	0.085023	m^3/kmol		
T	302.00	K		
	28.85	C		
	109.53	F		
P	345.42	at		
	35000.00	kPa		
	350.00	bar		
	5076.29	psi		
=8.134kJ/(kmol K) / 101.325 kPa				
	volume	P(bar)	error	mass
PreCharge	80.00	135	46225.00	11.84
Min	72.51	150	40000.00	0.006126
Max	35.93	350	0.00	0.003035
dV	36.59			
Rmax.	240.00			
Rmin.	203.41			

Figure 6 – Spreadsheet Example c

Figure 7 highlights the minimum and maximum molar specific volumes and change in volume, along with the values for the associated accumulator reservoir. Here the maximum reservoir volume is three times the accumulator pre-charge volume.

	volume	P(bar)	error	mass
PreCharge	80.00	135	46225.00	11.84
Min	72.51	150	40000.00	0.006126
Max	35.93	350	0.00	0.003035
dV	36.59			
Rmax.	240.00			
Rmin.	203.41			

Figure 7 – Spreadsheet Example d

The reservoir volume is described in terms of the accumulator volume by

$$V_r = V_{rmin} + \Delta V$$

The state of charge (SOC) is defined in terms of the volumes as

$$SOC = \frac{V_{max} - V_{in}}{V_{max} - V_{min}}$$

Note that the SOC is affected by V_{in} which has opposite meaning for the accumulator and reservoir.

6.0 SUMMARY/CONCLUSION

A method has been presented to size accumulator volumes in hybrid hydraulic applications with the accuracy of the BWR equation of state. Using a commonly available PC-based spreadsheet tool (Microsoft Excel), an optimization on a cost function (function of pressure) was employed. An accurate and complete solution was found even though the equation of state exhibited non-linear behavior. This method is simple, fast, cost effective, and adaptable to equations of state with higher complexity. While the actual energy stored is not calculated here—other tools are available using numerical integration techniques to calculate the stored energy

$$E_{stored} = \int p(V) dV$$

CONTACT

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REFERENCES

- [1] Parker Hannifin (www.parker.com), Hydraulic Accumulator Division, Brochure 1660-USA, pg. 53.
- [2] Bosch Rexroth Corporation (www.boschrexroth.com)
- [3] Otis, D.R., Pourmovahed, A., "An Algorithm for computing Nonflow Gas Processes in Gas Springs and Hydropneumatic Accumulators", *Journal of Dynamic Systems, Measurement, and Control*, March 1985, Vol. 107, pp. 93-94.
- [4] Cengel, Y.A., Boles, M.A., *Thermodynamics: An Engineering Approach*, 3rd Edition. McGraw-Hill, 1998, ISBN 0-07-115927-9, p. 85.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BWR – Benedict-Webb-Rubin

TACOM - U.S. Army Tank-automotive and
Armaments Command
TARDEC - TACOM Research, Development and
Engineering Center
NAC - National Automotive Center

**APPENDIX A – BOSCH REXROTH APPLICATION
NOTE**

See attachment.

1. Applications

Accumulators are devices used to store fluid power to do the following:

1. Store power for intermittent duty cycles thus economizing pump drive power
2. Provide emergency or standby power
3. Compensate for leakage loss
4. Suspension in vehicles
5. Dampen pulsations and shocks of a periodic nature

2. Principals of Operation

Most hydraulic systems require variable and intermittent flow rates. Energy can be saved by using the accumulator as a storage device to accept pump output flow when system demand is low and supplement output when demand is high.

Most accumulator designs are based on the principle that gas is compressible and oil is nearly incompressible. Assume an inert gas, such as nitrogen, is contained under pressure in a vessel. If hydraulic fluid is pumped into that vessel at a higher pressure than that of the original gas, the nitrogen compresses as its pressure rises to that of the fluid being pumped. This increase in gas pressure is proportional to the decrease in volume.

The vessel now contains energy in that the volume of hydraulic fluid, stored against the pressure of compressed nitrogen gas, if released, will quickly be forced out of the vessel under the pressure of the expanding gas.

Hydro-pneumatic accumulators with the gas separated from the liquid by a piston, diaphragm or bladder are by far the most common type.

To prevent auto ignition at high pressures, an inert gas such as dry nitrogen or helium should always be used.

Diaphragm and bladder type accumulators differ in the structural design of the elastic separator and the pressure vessel.

3. Sizing and Calculations

The majority of applications use accumulators to store energy for intermittent duty cycles or to provide a source of emergency power. In either case, the problem is determining the optimum size and precharge of the accumulator.

Accumulator sizing is based on the gas charge. The change in gas volume and pressure determines the amount of liquid that can be added or withdrawn. However, unlike mechanical springs, compressing a gas tends to heat it, raising the pressure above what would be expected from compression alone. Expanding a gas tends to cool it, reducing the pressure below that caused by expansion alone. Either of these effects can substantially affect accumulator sizing. Expansion (or compression) of a gas resulting in a change of gas temperature produces *adiabatic* expansion. When an accumulator is discharged rapidly, there is not enough time for sufficient heat transfer through the accumulator walls and adiabatic expansion occurs.

If the expansion (or compression) occurs slowly, there is sufficient time for heat to be added (or subtracted) by the accumulator wall to maintain a constant gas temperature and *isothermal* expansion occurs. The median of these two states of expansion can be partially "adiabatic".

When carrying out the calculations for an accumulator, the following pressures are of primary importance:

p_0 = Gas pre-charge pressure at room temperature and with liquid chamber drained

p_1 = Minimum operating pressure

p_2 = Maximum operating pressure

The following relationships apply: the gas pre-charge pressure is to be slightly lower than the minimum hydraulic pressure so that the bladder does not continually contact the oil valve (wear).

$$p_0 \approx 0.9 p_1 \quad (1)$$

The maximum hydraulic pressure is not to exceed 4 times the pre-charge pressure; otherwise, the elasticity of the bladder or diaphragm will be adversely affected. Also, excessive changes in pressure result in considerable heating of the gas. Reducing the pressure differential between p_1 and p_2 increases bladder service life. On the other hand, it must be taken into account that a lower pressure differential also reduces the utilization of available storage capacity.

Bladder-type accumulators

$$p_2 \leq 4 \cdot p_0 \quad (2.1)$$

Diaphragm-type accumulators

$$p_2 \leq 4 \cdot p_0 \quad (2.2)$$

Oil volumes

The gas volumes $V_0 \dots V_2$ correspond to the pressures $p_0 \dots p_2$. Here, V_0 is the rated volume of the accumulator.

The available oil volume ΔV corresponds to the difference between the oil volume V_1 and V_2 .

$$\Delta V = V_2 - V_1 \quad (3)$$

The variable gas volume for a given pressure difference is determined according to the following equations:

a) For **isothermal change of state** of gases, the following equation applies:

$$p_0 \cdot V_0 = p_1 \cdot V_1 = p_2 \cdot V_2 \quad (4.1)$$

The isothermal equation is used when the change in the gas volume takes place so slowly that there is sufficient time for the complete exchange of heat to take place between the nitrogen and its surroundings. The result is a constant temperature.

b) For **adiabatic change of state** of gases, the following formula applies:

$$p_0 \cdot V_0^n = p_1 \cdot V_1^n = p_2 \cdot V_2^n \quad (4.2)$$

n = relationship of the specific heats of the gas (adiabatic component); $n = 1.4$ for nitrogen. The equation for adiabatic change of state is used when the change in the gas volume takes place so rapidly that the temperature of the nitrogen also changes.

In most cases the changes of state tend to follow the adiabatic rather than the isothermal laws. It is often the case that the charge takes place isothermally and the discharge adiabatically. Considering the equations (1) and (2), ΔV is about 50 to 70% of the rated accumulator volume. The following formula can act as a guideline for sizing accumulators:

$$V_0 = 1.5 \dots 3 \times \Delta V \quad (5)$$

Calculation diagrams

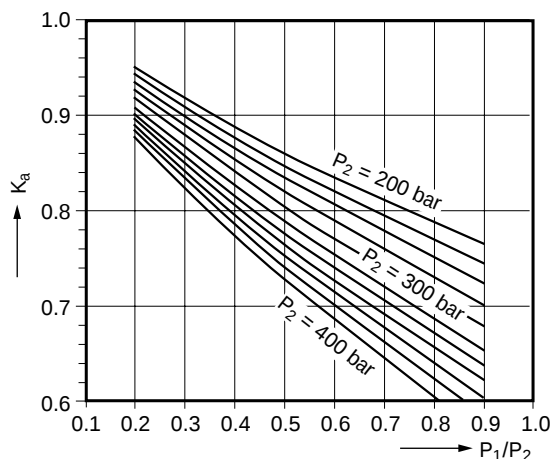
The formulae (4.1) and (4.2) are converted into diagrams on pages 4 to 6 for graphic calculation purposes. Depending on the type of problem, the available oil volume, the accumulator size or the pressures can be determined.

Correction factors K_i and K_a

The formulae (4.1) and (4.2) apply to ideal gases only. In practice, at pressures above 200 bar (2900 psi), the behavior of real gases deviates markedly from that of the ideal gases. This makes it necessary to use correction factors. These are to be taken from the following diagrams. The correction factors, with which the ideal discharge volume ΔV must be multiplied, are in the range of 0.6 ... 1.

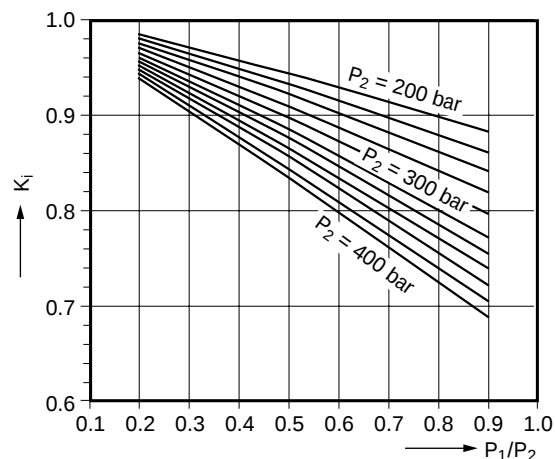
Adiabatic

$$\Delta V_{\text{real}} = \Delta V_{\text{ideal}} \cdot K_a$$



Isothermal

$$\Delta V_{\text{real}} = \Delta V_{\text{ideal}} \cdot K_i$$

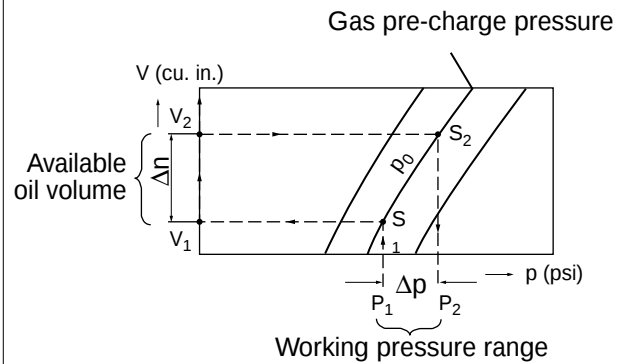


Using the Diagrams

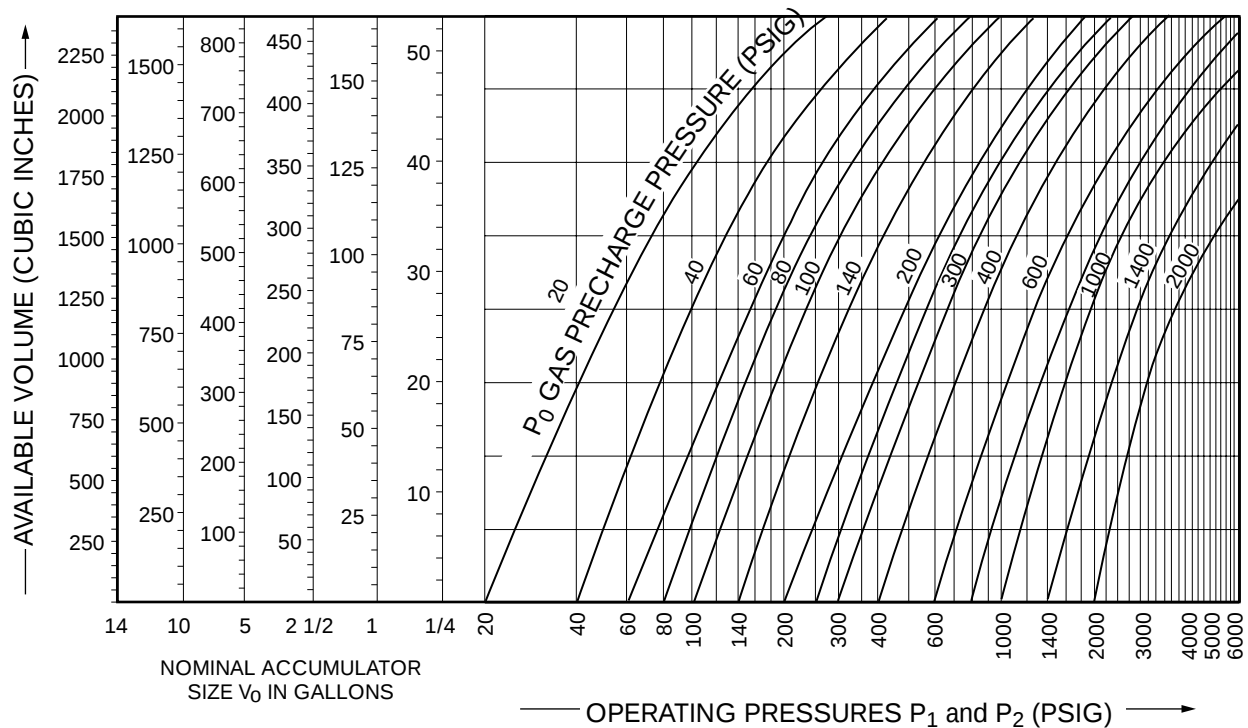
With the pre-charge pressure (p_0) and the minimum and maximum system pressures (p_1 and p_2) known, the available volume can be determined from the charts. Vertical lines are drawn from p_1 and p_2 to intersect the appropriate pre-charge curve. From the points of intersection, horizontal lines are then drawn to the left axis. Here V_1 and V_2 can be determined for the various sizes of accumulators. The difference between these values is the available volume.

Similarly, pressures can be determined if the volume is known.

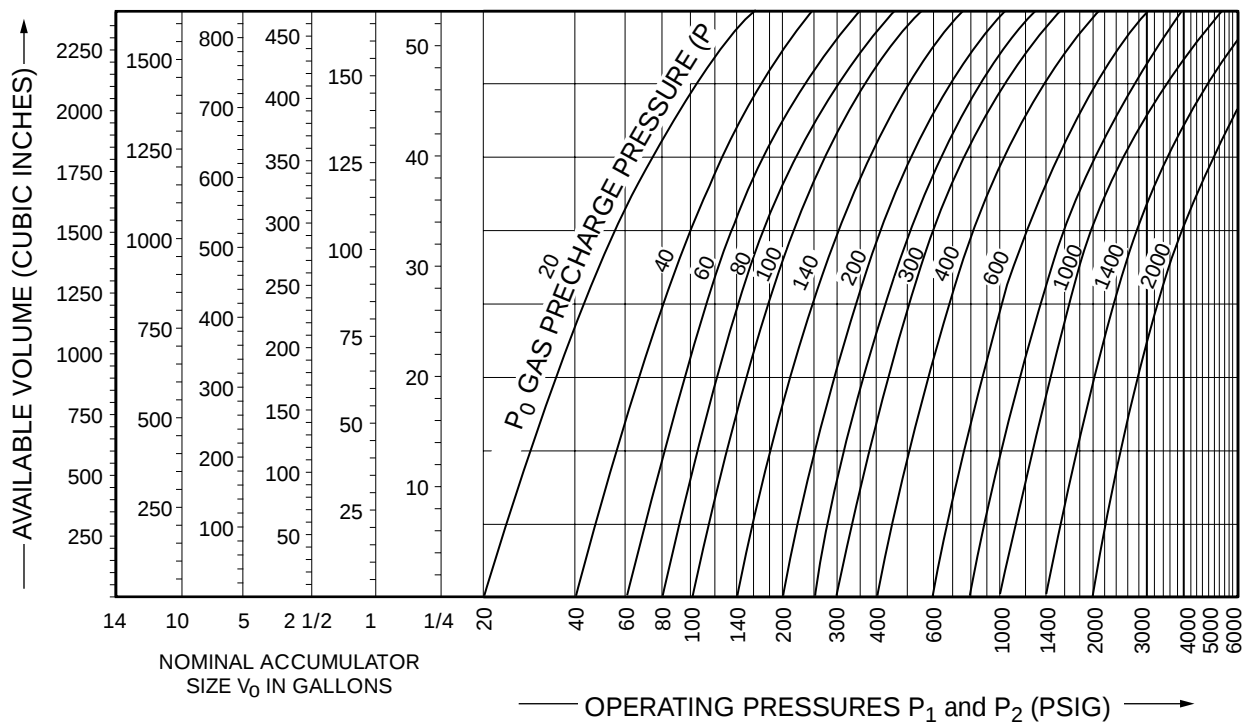
How to use the calculation diagrams



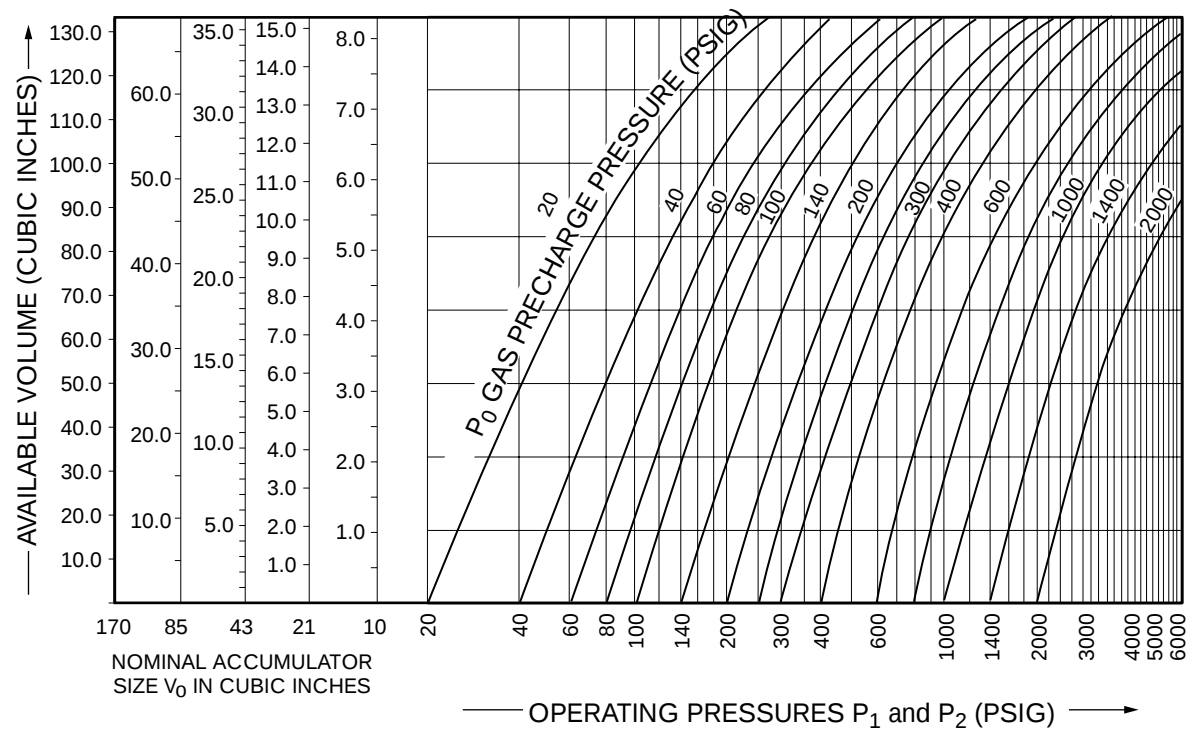
PRESSURE-VOLUME CURVE, ADIABATIC RELATIONSHIP, Bladder Type Accumulator



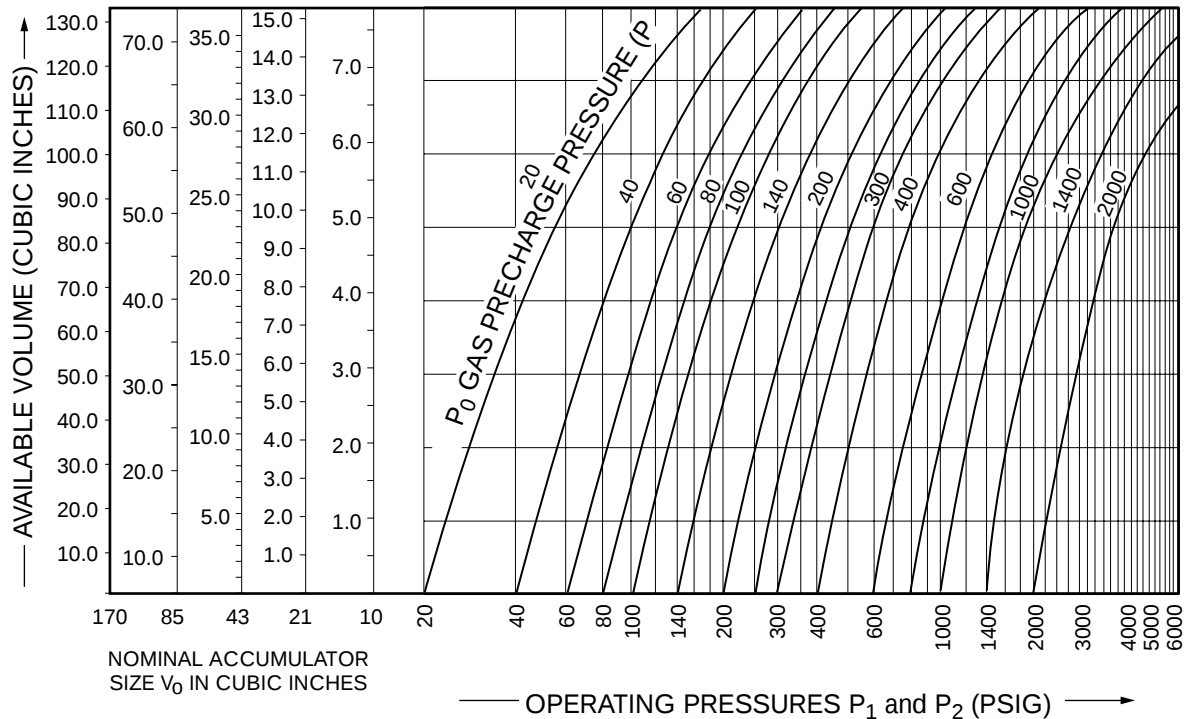
PRESSURE-VOLUME CURVE, ISOTHERMAL RELATIONSHIP, Bladder Type Accumulator



PRESSURE-VOLUME CURVE, ADIABATIC RELATIONSHIP, Diaphragm Type Accumulator



PRESSURE-VOLUME CURVE, ISOTHERMAL RELATIONSHIP, Diaphragm Type Accumulator



Installation and Operating Instructions

Mounting and Installation

BLADDER TYPE ACCUMULATORS MUST BE MOUNTED IN A VERTICAL POSITION WITH THE OIL VALVE AT THE BOTTOM. PLEASE CONSULT THE FACTORY IF OTHER MOUNTING POSITIONS ARE NECESSARY.

Mounting of Diaphragm Accumulators is unrestricted. All accumulators must be rigidly installed using clamps and support brackets specifically designed for accumulator mounting. Oil valve ports must not be used to support the weight of the accumulator.

CAUTION - DO NOT use gas or oil valves as lifting points. The accumulator shell is a pressure vessel and must not be altered. **DO NOT** weld or machine pressure vessels.

Improper installation may result in damage to the oil or gas valve, accumulator shell, or seals. Exercise care not to paint over rating nameplate or the warning label.

General

Hydraulic circuits incorporating accumulators may store hydraulic oil under pressure depending on the function of the accumulator in the system. Therefore, the system may remain pressurized after the pump is turned off.

CAUTION - Prior to performing any maintenance or system modifications, bleed off any stored system pressure.

Completely release all hydraulic fluid pressure in a safe controlled manner using appropriate valving. Installation of an automatic accumulator discharge valve in the hydraulic circuit is recommended.

Accumulator repairs must be performed by trained hydraulic service personnel experienced in servicing accumulators. Contact your local authorized distributor for application or repair assistance.

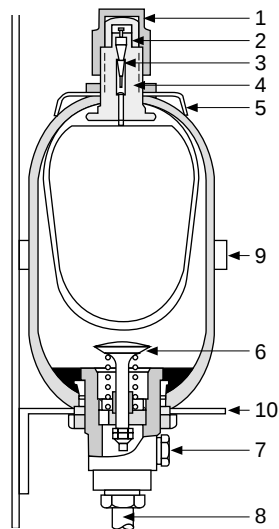
Bladder accumulators

Bladder type are generally delivered with a nitrogen pre-charge pressure of approximately 50 psi (3 bar). After installation and prior to initial start-up, the pre-charge pressure (p_0) must be set to the application requirements, or machine manufacturer's specifications.

Diaphragm accumulators

Diaphragm type are generally delivered without pre-charge pressure. The pre-charge pressure must be set to the application requirements or machine manufacturer's specifications prior to initial start-up.

CAUTION - Improper accumulator pre-charge may result in decreased life or failure of the bladder or diaphragm.



* Tightening torque for valve guard
175–350 lb-in (20–40 Nm)

FIG.1

- | | |
|-------------------|---------------------|
| 1. Valve guard* | 6. Poppet valve |
| 2. Valve cap | 7. Gauge port |
| 3. Gas valve core | 8. Hydraulic line |
| 4. Gas valve body | 9. Clamp |
| 5. Name plate | 10. Support bracket |

Checking the gas pre-charge pressure

Bleed off hydraulic system pressure. After the accumulator has been put in service, the pre-charge pressure (p_0) should be checked with an accumulator charging and testing device at least once in the first week. If this check reveals no loss in pressure, the pre-charge should be checked on the following schedule:

1 st Check	1 week
2 nd Check	3 months
3 rd Check	1 year
4 th & Continued	yearly

If the gas pre-charge is low, investigate cause and correct. Possible causes of lost pre-charge pressure include leaking or damaged gas valve, or damaged bladder.

Testing pre-charge pressure " p_0 "

Completely release accumulator hydraulic system pressure in a safe controlled manner. Install the charging and testing device onto the gas valve (see Fig. 1, Item #4). While depressing the button on the charging device, the gauge will indicate the gas pressure.

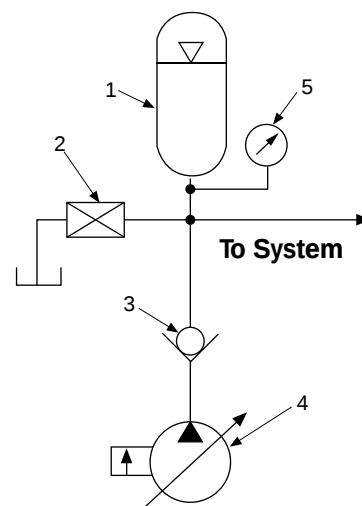


FIG.2 Typical Circuit

- | | |
|---------------------------------------|-----------------------|
| 1. Accumulator | 3. Check valve |
| 2. Bleed or automatic discharge valve | 4. Pump |
| | 5. Oil pressure gauge |

Charging the accumulator

CAUTION - USE only NITROGEN for charging accumulators. NEVER USE OXYGEN OR AIR, due to the risk of explosion.

Close the drain valve on the charging and testing device and connect the hose to the nitrogen bottle.

Remove the valve guard and cap and screw the charging and testing device onto the gas valve. More detail information is provided in the instruction sheet furnished with the charging and testing device. Open the gas shut-off valve on the nitrogen bottle and allow the gas to flow slowly into the accumulator. Close the shut-off valve frequently and check the value on the pre-charge by depressing the button on the charging device.

If the pre-charge pressure is too high, it may be reduced by opening the drain valve and carefully depressing the button on the charging device.

NOTE: The pre-charge pressure will vary depending on the gas temperature. Once the desired pre-charge is reached, it is necessary to wait 2 minutes until the gas temperature has equalized. Once again the pre-charge pressure needs to be checked and adjusted if necessary.

Unscrew the charging and testing device and replace the valve guard and cap (see Fig. 1, Items #1 & 2) and torque to specifications. A check for leaks with a soapy solution should follow. If a leak is found, it should be repaired following recommended repair procedures. If the gas valve core is replaced, use only valve cores approved for accumulator service, NEVER USE AN AUTOMOTIVE TYPE VALVE CORE.