



Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

By Richard R Larsen PE

Maintenance-free, gas-charged accumulators, reservoirs, hydraulic shock arresters and the like that are required to have an operating life in years or tens of years are usually made with welded bellows because the impermeable nature of modern alloys to helium and larger molecules makes it possible to envelop the gas charge entirely with metal, obviating the permeation that would occur through elastomeric seals (o-rings, etc.). To construct an “impermeable” assembly means to achieve a leak rate so far below our needs that the device functions to specifications throughout its anticipated life. This requires knowledge of the behavior of fine leaks—how to detect them, how to quantify them, how to prevent them. This paper discusses the issues involved in achieving virtually leak-free devices using welded bellows, the characteristics of fine leaks and how Flexial can predict operational life of such devices in decades of years.



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White Paper

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Leakage and long-term gas containment in a welded bellows accumulator or reservoir

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LEAKAGE AND LONG-TERM GAS CONTAINMENT IN A WELDED BELLOWS ACCUMULATOR OR RESERVOIR

Introduction

A maintenance-free, gas-charged device would ideally have zero leakage throughout its life, and this is unquestionably the principal reason for constructing such units with a metallic bellows and metallic containment. The impermeable nature of metals to helium and larger molecules makes it possible to envelop the gas charge entirely with metal, obviating the permeation that would occur through elastomeric seals (o-rings, etc.). A typical welded bellows accumulator or reservoir can have 1,000 to 10,000 or more inches of microscopic bellows weld and several containment assembly welds, electrical connectors, gas charge port and other potential leakage zones. Nevertheless, permanently gas-charged accumulators, reservoirs, surge arresters and other devices utilizing welded bellows have a history of lasting for decades in service with no perceptible decay in performance. After saying this, we must bear in mind that everything has the potential to leak. To construct a maintenance-free accumulator means to achieve a leak rate so far below our needs that the device functions to specifications throughout its anticipated life—in many cases, 30 years. This requires knowledge of the structure of microchannels across bellows welds and the behavior of fine leaks—how to detect them, how to quantify them, how to prevent them.

This paper is organized into the following topics:

- Periods of study of fine leaks
- Types of leak flow regimes
- The structure of fine leaks in welded bellows leakage microchannels
- Materials prone to develop microchannel leak paths
- Comparison of leak rates of various charge gases
- Effects of bellows flexure on fine leaks
- Effects of liquids on fine leaks
- Pressure loss over time through fine leaks

Periods of study of fine leaks

At the core of study of fine leaks is the only instrument capable of detecting them, the helium mass spectrometer. The helium-tuned mass spectrometer (MST) was developed at Oak Ridge National Laboratory, Oak Ridge, Tennessee, in 1944. It was developed to determine the absolute integrity of gas systems at the K-25 facility that processed uranium U-235 from uranium pentoxide gas. The MST underwent several evolutions from an all-glass, frangible device to the metal system in use today.

1955—1970 The first period of extensive study of fine leaks using the MST was primarily by NASA and the military to achieve high integrity of spacecraft tanks, valves,

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

conduits and other gas and fluid apparatus, including formed and welded bellows. This represented the beginning of vacuum science in the ultra-high vacuum range.

1970—1990 Studies by electronic equipment manufacturers developing miniature cases for transistors, LEDs, pressure sensors and microcircuits. These packages are extremely small volume and charged to one atmosphere with helium as an inert tracer gas. The nature of most studies was how to detect the presence of a fine leak that could allow the diffusion of gases—particularly water and oxygen—into the package as the internal helium charge gas diffused out. Most of the studies were at molecular flow rates with pressures ranging from sub-atmospheric to two or three atmospheres. The findings have been of marginal usefulness in characterizing welded bellows leaks.



Laser welded TO-18 package, above, and integrated circuit in TO-3 package shown open and welded closed.

1990—PRESENT A new wave of flow studies surrounds the development of MEMS hardware. MEMS development is heavily focused on performing operations done by current hardware, but on a micro-scale. Researchers are redefining the behavior of molecules at these scales. Flow through microchannels is quite different from the macro-scale of present fluid equipment. Interatomic forces, surfaces, and fluid dynamics do not precisely follow the existing governing equations—Boltzmann, Navier-Stokes, Knudsen and others—and require modifications.^{1 2} This new wave of studies has afforded some clarification to the behavior of gas flow from fine leaks through the very thin walls of welded bellows diaphragms. Even though most of the microchannels under study in the MEMS regime are roughly a decade larger than the apparent leak typical of a welded bellows, the results more closely define bellows leakage behavior and are far more applicable because they study multiple atmospheres of differential pressure.



MEMS escapement and gears etched in silicon

Three flow ranges of gas leakage

In this next section, we have reduced flow to three ranges: molecular, transitional and viscous. We realize that flow regimes are better expressed as free molecular, transitional, slip and continuum (viscous), but since we are only concerned with molecular flow, we will lean to simplicity. Listing from largest to smallest:

¹ Tang, G.H., et al, Experimental study of compressibility, roughness, and rarefaction influences on microchannel flow, Xi'an Jiaotong University, PR China, Elsevier.com.

² Tison, S.A., Experimental data and theoretical modeling of gas flows through metal capillary leaks, NIST, from *Vacuum*, vol 44, 1993, p1172.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

- **Viscous or Poiseuille flow** exists when differential pressure across the leak path typically exceeds one atmosphere.^[3] Most accumulators and reservoirs are charged in excess of one atmosphere which would seem to make this the most common case, but microchannel studies have shown why we can have high pressure differentials and still have flow in the molecular range.⁴

Several conditions can define viscous flow:⁵

- When system pressure is greater than 10^{-3} atmospheres
- When $DP_{avg} > 600 \mu\text{-cm}$, where D is the smallest dimension of the microchannel and P_{avg} is the average pressure in microns of mercury.
- When mfp/D is less than 0.01, where mfp is the mean free path of the gas and D is the smallest dimension of the leak channel
- Where the Knudsen number (Kn) is less than .01

With viscous leak rates on the order of $10^{-3} \text{ atm cm}^3/\text{sec}$ and greater, we transition out of MST and can use bubble testing, sonic testing, pressure decay and other methods to detect leakage.

- **Transitional flow** is leakage greater than molecular flow, but less than viscous flow. It is a combination of molecular flow and viscous flow, the definitions of which are empirical and variously defined. In transitional flow, molecules collide with both the leak channel wall and with each other. Transitional flow is common in welded bellows MST leak detection and occurs in the leakage range of 10^{-4} to $10^{-7} \text{ atm cm}^3/\text{sec}$.⁶

Several conditions can define transitional flow:⁷

- When system pressure is less than 10^{-3} atmospheres and greater than 10^{-5} atmospheres
- When $DP_{avg} > 10 \mu\text{-cm}$ and $< 600 \mu\text{-cm}$, where D is the smallest dimension of the microchannel and P_{avg} is the average pressure in microns of mercury.
- When MFP/D is between 0.01 and 1.0, where MFP is the mean free path of the gas and D is the smallest dimension of the microchannel
- Where the Knudsen number is between .1 and 10. (We should note that flow between $Kn = .01$ and .1 is defined as slip flow.)

- **Molecular flow** is the lowest leak range. It always occurs at low differential pressures of one atmosphere or less where the cross-sectional area of the leak path is very small compared with its length (a long, slender tube or twisting path), and

³ Greenhouse, Hal, Hermeticity of Electronic Packages, Allied Signal Corporation, 2000, p34.

⁴ Tang, p2290.

⁵ Greenhouse, p17.

⁶ Marr, J.W., Leakage Testing Handbook, NASA Report no. CR-952, 1969, p6-4.

⁷ Greenhouse, p17.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

where the MFP of the gas molecules is greater than the greatest transverse dimension of the leak channel.^{8,9} However, we can also have the *equivalent* of molecular flow at high differential pressures as shown by Tang, Tison and Beskok, and as we will discuss.¹⁰ The MFP of the molecules increases as pressure decreases (fewer molecules allow a greater MFP), so molecular flow typically occurs under vacuum conditions where pressure is less than one atmosphere. This is typical of the condition that exists during mass spectrometer leak testing (MST). In mass spectrometer leak testing of bellows, this is the usual form of leak that is detected when the leak is smaller than 1×10^{-7} atm cc/sec helium. Most welded bellows products are specified at this leakage level or less. In molecular flow, virtually all collisions are between the molecule and the wall of the leak channel while collisions between molecules is almost non-existent. In molecular leak channels, molecules can also bounce back upstream because, while the surface may appear mirror-smooth, the surface irregularities are dimensionally far greater than the size of the molecules.

Several conditions can define molecular flow:¹¹

- When system pressure is less than 10^{-5} atmospheres as in mass spectrometry
- When $DP_{avg} < 10 \mu\text{-cm}$, where D is the smallest dimension of the leak channel and P_{avg} is the average pressure in microns of mercury.
- When MFP/D is > 1.0 , where MFP is the mean free path of the gas and D is the smallest dimension of the leak channel
- Where the Knudsen number is 10 or greater.

Summing up the three flow ranges of leakage and how they apply to gas-charged welded bellows devices: Because leak rates for gas-charged accumulators and reservoirs must be non-existent or extremely small to yield thirty years of service at 10 to 150 or more atmospheres of pressure, acceptable leak rates will invariably be less than 10^{-7} atm cm^3/sec helium and more than likely on the order of 10^{-8} atm cm^3/sec helium or less. How much leakage can be tolerated will depend on the initial gas volume and how much gas loss is allowable and the device continue to function. This will almost invariably require that a gas-charged device with any detectable leakage must have that leakage in the molecular flow range.

Diffusion in molecular leaks: In molecular-size flow channels, if there is a density gradient of a particular gas—e.g., if the bellows is pressurized with helium inside and atmosphere exists outside with atmospheric oxygen and nitrogen outside but not inside—

⁸ Marr, p6-9.

⁹ Greenhouse, Hal p63

¹⁰ Beskok, Ali, <http://www.cfm.brown.edu/people/beskok/>, and personal communication.

¹¹ Greenhouse, p17.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

the gases on the outside will tend to flow inward to reduce the gradient. This means that if a leak is present that is leaking the charge gas out by molecular flow, it is also leaking atmosphere inward, albeit slowly. In time, we will begin to find traces of atmospheric gases inside the bellows even though none existed during manufacture. While in most accumulator and reservoir applications this is insignificant, in some processing applications, and especially in semiconductor, electronic and ultra-high vacuum applications, this could present serious contamination issues. It is not unusual in these cases to specify leakage rates in the 10^{-10} atm cc/sec range to prevent such diffusion.

Fine leaks appear to be molecular in form:

Leaks in bellows welds typically indicate as molecular. We can say this because in the manufacture of welded bellows, leakage rates are usually specified near the upper limits of sensitivity of a mass spectrometer because weld reliability is high. For most materials, the reality is that leakage in welded bellows is typically undetectable—that is, mass spectrometry rarely shows a leak unless the leak is gross and the vacuum system will not reduce the pressure low enough to initiate a test. As was stated earlier, it is rare that the permissible leak rate of a welded bellows be larger than 1×10^{-7} atm cc/sec. Most applications are specified at this rate or less. We noted that, per Marr, leaks smaller than this value are molecular rather than transitional.¹² That was the convention until studies began for MEMS engineered devices and fine capillaries where higher differential pressures still exhibited low flow in microchannels, a condition we have experienced with pressurized welded bellows devices for decades. Quoting Tison from his paper in 1993:

Due to the lack of theoretical or experimental models for the flow of gases through tubes with high pressure differentials ($P \approx \Delta P$) in the transition flow regime, quite often, models developed for low pressure differentials ($P \gg \Delta P$) are utilized. // To model the flow through tubes with high pressure differentials, it would be advantageous to know the relationship between the conductance of the tube and some predictor, such as the mean free path of the gas. It is unclear from the literature which functional form best applies to the described problem, although the Knudsen form seems to be the most widely applied.¹³

Modeling the flow path as molecular

Molecular flow, as we observed, exists when the cross-section of the leak path is smaller than the mean free path of the molecules in the flowstream. To confirm that we have molecular flow in a bellows weld, let us determine the approximate diameter of a leak channel that is leaking at 10^{-7} atm cc/sec in a bellows with a diaphragm thickness of 0.013 cm (approx. 0.0050 inch). We can compare this

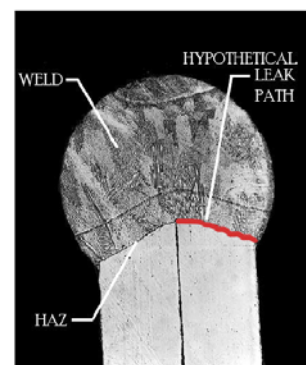


Figure 2

¹² Marr, p6-4.

¹³ P1172.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

cross-sectional dimension to the mean free path of a charge gas at several pressures to see if flow remains molecular. Let us imagine a leak path near the heat affected zone (HAZ) of a bellows weld something like shown in figure 2. Note that the red line is shown *greatly* exaggerated in size over actual dimensions.

From Greenhouse, we can use the formula for molecular conductance in a long, cylindrical tube.¹⁴ The actual leakage path of a welded bellows leak would not be this convenient; it would be a tortuous, twisting path wrapping around metal grains and through grain boundaries with a length considerably greater than the diaphragm thickness. For sake of discussion, let us say it is as short as possible, i.e., equal to material thickness, and let the system be near room temperature. We will use helium with a mass of 4 as our gas, 20°C (68°F or 293°K) as operating temperature. The molecular conductance or leakage flow is expressed as:

$$\text{Eq. (1)} \quad F_m = \frac{3.81D^3 \sqrt{\frac{T}{M}}}{l} \text{ in liters/sec.}$$

Solving for D, we get Greenhouse's formula shown in Eq. (2):

$$\text{Eq. (2)} \quad D^3 = \frac{F_{mc}(l)}{3.81 \sqrt{\frac{T}{M}}}$$

$$\text{Substituting: } D^3 = \frac{(1 \times 10^{-10})(0.013)}{3.81 \sqrt{\frac{293}{4}}}$$

$$D = 3.42 \times 10^{-5} \text{ cm}$$

Now, compare this incredibly small cross-sectional dimension of our 10^{-7} bellows leak with the mean free path (MFP) of the charge gas at various pressures. Increasing pressure shortens the MFP because more molecules are present, so we will consider a range of increasing pressures. We can calculate the MFP for helium and argon at various pressures as:¹⁵

¹⁴ Greenhouse, p38, Eq. (2-15)

¹⁵ Greenhouse, p25, Eq (1-12).

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

Eq. (3)
$$MFP = \frac{kT}{\sqrt{2} \cdot \pi P \sigma^2}$$

Where the pressure is in cgs units, dynes/cm²:

One atmosphere = 1.013 x 10⁶ dynes/cm²

Assume temperature $T = 70^\circ\text{F} = 294^\circ\text{K}$

$k = 1.38 \times 10^{-16}$ dyne-cm/deg

σ = molecular diameter: He = 2.2 x 10⁻⁸ cm; Ar = 3.7 x 10⁻⁸ cm.

For a range of pressures from 0.1 to 75 atmospheres, using Eq. (3), we get the following mean free path values shown in Table (1) for helium and argon:

Table (1) Mean free path of helium and argon at room temperature vs. pressure

P _{atm}	MFP He	MFP Ar
0.1	1.86E-04	6.59E-05
0.5	3.73E-05	1.32E-05
1	1.86E-05	6.59E-06
2	9.32E-06	3.29E-06
3	6.21E-06	2.20E-06
4	4.66E-06	1.65E-06
5	3.73E-06	1.32E-06
10	1.86E-06	6.59E-07
20	9.32E-07	3.29E-07
40	4.66E-07	1.65E-07
60	3.11E-07	1.10E-07
75	2.49E-07	8.79E-08

MFP Observations:

1. For helium from one atmosphere and up, the MFP is shorter than the channel diameter, and for argon from a half atmosphere and up we get the same results. *As we reach 20 atmospheres, we are well into the definition of transitional flow and at 75 atmospheres we are moving into the viscous or continuum regime.* Clearly, the flow is not molecular by definition.
2. For a colder temperature of -40°C, the MFP decreases 20% and we move further into the transitional or viscous range.

Equivalent molecular flow at high differential pressures

Beskok recommends that in cases of high differential pressure, the microchannel be modeled for local Knudsen number at the inlet and exit of the microchannel and the results compared with normal flow regimes.¹⁶ At the exit, we will always have either free molecular flow (fm) if on the mass spectrometer or transitional flow if in air. Based on

¹⁶ Personal communication by writer with Ali Beskok, 10-21-09.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

the definition of choked flow as flow reaching sonic velocity, the prediction is that this would occur abruptly near the inlet and would have a constant mass flowrate even with varying pressures.¹⁷ The writer speculates that given the greatly irregular shape and size of the microchannel, this could occur repeatedly at various points in the channel depending on the size of the constrictions, and each constriction would present a fixed pressure drop.

Another contributing factor to achieving equivalent molecular flow at high pressure differentials is surface roughness. Tang, et al, observed in their own studies of stainless steel tubes that surface roughness was significantly higher than theoretical predictions:

“...the friction factor for stainless steel tubes is significantly higher than the theoretical prediction for conventional sized tubes. In the laminar regime, the friction factor is about 28%, 33%, 55% and 70% higher for the tubes of $D = 300, 260, 172$ and $119 \mu\text{m}$, respectively. We attribute this result to surface roughness effect. Comparing the cross-sections and longitudinal sections of the SEM photos for the stainless steel tubes with the fused silica tube or square channel shown...we find tht the inner surface of the stainless steel tubes is very irregular and many concavo-convex particles are present...”¹⁸

While the tubes referenced are significantly larger than the microchannel we formulated, and the surface roughness of drawn capillaries is not the same as the irregular form of a leak channel, the surface roughness findings appear to reflect the same end result of strong flow resistance.

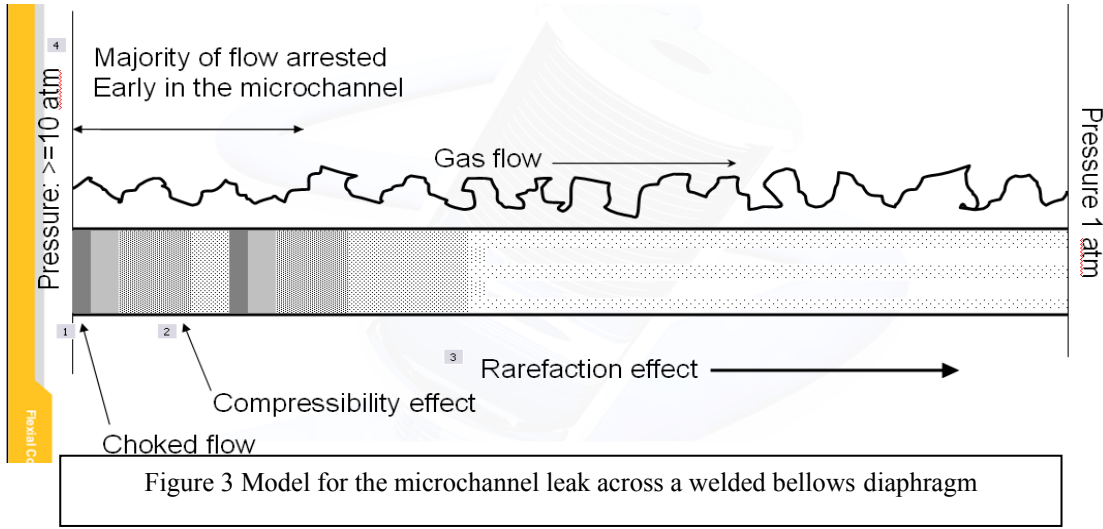
A third contributing factor that may be significant in microchannel gaseous flow is rarefaction.¹⁹ Our calculation of Knudsen numbers range from $\text{Kn} = .004$ at the inlet to $\text{Kn} = 5$ at the outlet. The latter is an apparent effect. Given that the flow regime at regions along the microchannel fall between $0.1 < \text{Kn} < 10$, the transitional flow regime, rarefaction must be considered. Since most of the flow restriction is believed to occur near the inlet and at a few points in that region, rarefaction appears to be most probable from that region down toward the exit.

¹⁷ Karniadakis, George, and Beskok, Ali, *Microflows and Nanoflows: Fundamentals and Simulation*, 2000

¹⁸ Tang, p2290.

¹⁹ Tang, p2292.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009



A suggested model for the microchannel leak across a welded bellows diaphragm is given in Figure 3 above.

Comparison of leak rate of different gases through the same leak channel:

Let us consider how different gases will pass through a fine microchannel leak at the same temperature. Here, the molecular weight of the gas determines the flow rate and the leakage difference is proportional to the square root of the ratio of their molecular weights. The heavier the molecular weight, the slower the flow. Using Greenhouse's equation (3-6), we find:

$$\text{Eq. (4)} \quad L_1 = L_2 \sqrt{\frac{M_2}{M_1}}$$

Where:

- L1 = the true leak rate of gas 1
- L2 = the true leak rate of gas 2
- M1 = the molecular weight of gas 1
- M2 = the molecular weight of gas 2

For example, we find a fine leak in a bellows accumulator of 2×10^{-8} atm cc/sec of helium with the mass spectrometer. We are going to charge the assembly with argon. The pressure and temperature conditions are as we have shown above, i.e., the fine leak will remain molecular. What will the leakage rate be with argon as the charge gas?

$$L_{\text{argon}} = L_{\text{helium}} \sqrt{\frac{M_{\text{helium}}}{M_{\text{argon}}}} = L_{\text{helium}} \sqrt{\frac{4}{40}} = (.316)L_{\text{helium}} = 6.3 \times 10^{-9} \text{ atm cc/sec}$$

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

Argon will leak at about 32% of the rate of helium, nitrogen at 38%. Any two gases can be compared by finding the square root of the ratio of their molecular weights.

Effect of bellows flexure on a bellows weld leak:

The predictability of a fine leak as given in the examples above presumes that the granular structure of the metal surrounding the leak path is immobile. However, this is not the case with welded bellows that, like springs, are among the most highly flexed metallic devices made. Welded bellows are deliberately designed for a high degree of flexure of the alloy from which they are fabricated. And the greatest flexing is in the region of greatest strain—near the HAZ at the ID and OD. This flexure can be mechanically-induced as in stroking the bellows, or pressure-induced as in cycling the pressure up and down. When the grains surrounding a fine leak are flexed, predictability is lost. Leak channels, when they exist, are usually through the grain boundaries. The leak channel, despite its incredibly small size—perhaps only fifteen or twenty times the diameter of the gas molecule—can change size and shape, and thus its leak rate. If a bellows with a known leak is to be used, it should be exercised through its mechanical and/or pressure regimen while under mass spectrometer leak test to determine if the leak rate will change under these circumstances. The worst-case rate should then be used to determine loss of charge gas and the effect on its application.

Let us consider an example of this in a production linear seal that provides 4 in. (10 cm) of axial motion in pressurized high voltage switchgear. The conditions are:

- Material: Heat treated AM-350, 0.007 in. thick diaphragms (0.18 mm)
- Operating pressure: 7 atm SF₆ external to the bellows

In this application, an occasional leak was masked during MST. The solution was to fully pressurize the bellows assembly to 7 atm with helium with the opposite side on the mass spectrometer under test. Then fully exercise the bellows through its flexural operating range mechanically. The result has been to isolate a leak in excess of 10^{-7} cm³/sec helium in about every 360,000 inches of weld (roughly one assembly per 1000).

Effect of liquids on microchannel leaks through bellows diaphragms

Any liquid coming in contact with a microchannel leak will close the leak. Even skin oil only microns thick will mask a helium MST indication and block gas flow through the channel. If the liquid contacts the inlet side, closure will be permanent, especially if the liquid is comprised of larger molecules of low volatility such as oils. Contact of a microchannel by a liquid on the exit side may be permanent depending on volatility, molecular size and pressure differential across the channel. High volatility materials such as isopropanol and acetone and even water can be drawn into the channel by surface tension and remain trapped. These higher volatility liquids may be removed from the microchannel by baking under vacuum, but may not become unblocked by standing in air at room temperature.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

Vogt Valve division of Flowserve has observed that even large leaks in valve bodies under high pressure were blocked by water.²⁰ They report that a valve body with a dry air leak of $.28 \text{ cm}^3/\text{sec}$ at 500 psi during air testing would not leak water in any reasonable time period. Further a dry air leak of $1.25 \text{ cm}^3/\text{sec}$ at 2000 psi would also not leak water in any reasonable time period. And of significance, water permanently closed the leak to any further air leakage until the valve body was baked out by a high temperature furnace soak. Speculation is that surface tension of the liquid bridges larger leak paths. The effect is greater on non-circular, slit-type channels than on circular ones. Molecular size effectively reduces the size of the microchannel to molecular flow proportions and permanently impedes gas flow.

While this effect is detrimental to finding leaks in bellows, it can be useful in containing and permanently blocking off microchannel leaks over the life of the accumulator or reservoir. It can serve as an added assurance where an extremely small leak might be missed during testing.

Gas loss through a molecular leak and residual pressure:

Since we can state that a fine leak is molecular in its flow behavior, we can use the worst-case finding to determine how much gas will leak out over time and what the residual pressure will be. Since the loss is extremely small, we do not need to integrate the effect of pressure change on the loss.

Example:

Consider an accumulator with a gas volume of 1600 cc (approx. 976 in^3) and a charge pressure of 8 atmospheres. If the accumulator was found to have a leak rate of 1×10^{-8} atm cc/sec helium after fabrication, how much helium gas would it lose in 15 years for several leak rates? Since from what we have just seen we can state that the leak is molecular, then gas loss is approximately constant, although to be more precise, we would have to integrate the results to account for the slight loss of pressure. Fifteen years = 4.73×10^8 seconds. We get the approximate results shown in Table (2):

Leak rate	loss cc	loss in^3
1×10^{-7}	47.3	2.9
1×10^{-8}	4.7	0.3
1×10^{-9}	0.5	0.03

We can use these figures for helium to calculate the leakage rate of other gases by calculating the square root of the ratio of molecular weights per Eq. (4).

²⁰ Jolly, Guy, Vogt Valves: A treatise on leakage, Flowserve, FCD VVABR1013-00 01/05

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

Summary:

In welded bellows accumulators and reservoirs, leakage is usually so small as to not be detectable with a helium mass spectrometer sensitive in the 10^{-9} std cm³/sec range or even lower. In those rare conditions where leakage is detected, it is usually molecular and does not exceed 1×10^{-7} atm cc/sec helium. Otherwise, it is usually so gross (e.g., an unwelded section) that the mass spectrometer will not shift into the test mode and the error can be seen visually.

When leaks that test in the molecular range on a mass spectrometer are pressurized with multiple atmospheres of pressure across the diaphragms, they can continue to test as if they were molecular. This behavior has been noted since welded bellows were first developed, but only recent studies of gas flow in microchannels has begun to explain the phenomenon. The conditions of choked flow, compressibility and rarefaction appear to present resistance to flow in a manner that somewhat disregards pressure differentials. And the highly irregular surfaces and contours of microchannels in metals such as stainless steel appear to further attenuate flow or perhaps constitute the resistance itself.

We can compare the leak rates of various gases and predict how a leak described by helium will behave in argon, nitrogen or other gases.

Bellows flexure can make a known leak behave differently or even mask the leak altogether. Strain on the grains surrounding the microchannel path can drastically alter the rate of flow.

Liquids and even fine films of liquids will immediately block a microchannel leak and the blockage can be permanent. This can mask a fine leak and prevent its detection altogether. Conversely, a liquid can permanently block a microchannel leak and prevent or greatly attenuate loss of charge gas by reducing the molecular diameter of the microchannel—a desirable condition for long-life, maintenance-free devices.

We can predict what the loss of gas through a fine leak will be over time, even if the leak is not truly molecular, but behaves as molecular.

Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

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Leakage and long-term gas containment in a welded bellows accumulator or reservoir 2009

Abstract

Maintenance-free, gas-charged accumulators, reservoirs, hydraulic shock arresters and the like that are required to have an operating life in years or tens of years are usually made with welded bellows because the impermeable nature of modern alloys to helium and larger molecules makes it possible to envelop the gas charge entirely with metal, obviating the permeation that would occur through elastomeric seals (o-rings, etc.). To construct an “impermeable” assembly means to achieve a leak rate so far below our needs that the device functions to specifications throughout its anticipated life. This requires knowledge of the behavior of fine leaks—how to detect them, how to quantify them, how to prevent them. This paper discusses the issues involved in achieving virtually leak-free devices using welded bellows, the characteristics of fine leaks and how Flexial can predict operational life of such devices in decades of years.