

Vogt Valves: A Treatise on Leakage

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A Treatise on Leakge

Nomenclature

Unless otherwise stated, all symbols used in this article are defined as follows:

Symbol	Meaning
d	Internal diameter of pipe/capillary, in inches.
D	Internal diameter of pipe/capillary, in feet.
f	Friction factor for piping.
g	Acceleration of gravity = 32.2 feet per second per second or 32.2 ft/sec ² .
h _L	Loss of static pressure head due to fluid flow, in feet of fluid.
K	Resistance coefficient or velocity head loss in the formula $h = KV^2/2g$.
K _L	Resistance coefficient for leak path for use in laminar flow equation.
L	Length of pipe, in feet.
L _i	Length of capillary/pipe, in inches.
q _s	Rate of liquid flow, in cubic inches per second at flowing conditions.
q' s	Rate of gas flow, in cubic inches per second at standard conditions (14.7 psia @ 60°F).
Q _g	Leakage rate of gas across a leak path, in cubic inches per second at standard conditions (scis, 14.7 psia @ 60°F).
Q _L	Leakage rate of liquid across a leak path, in cubic inches per second at flowing conditions.
m	Molecular weight of gas.
P	Pressure, in pounds per square foot.
P' a	Average pressure across a capillary/pipe or leak path, in pounds per square inch absolute (psia).
R _e	Reynolds number
S _g	Specific gravity of gas relative to air = the ratio of the molecular weight of the gas to that of air.
v	Mean velocity of flow, in feet per second.
ΔP	Differential pressure across capillary/pipe or leak path, in psi.
MU (μ)	Absolute (dynamic) viscosity, in centipoise.
RHO (ℓ)	Weight density of fluid, in pounds per cubic foot. For water = 62.4 lb/ft ³ .
SIGMA (σ)	Surface tension of liquid to air interface, in lb/ft.
}	Proportional to...

Abstract

Laminar type leakage across leak paths occurs with such a frequency that countable “drops” of liquid or “bubbles” of gas leakage can be observed and volume determined. Some leak paths will leak gas but will not leak a liquid such as water.

This paper discusses the theoretical aspects of liquid and isothermal gas laminar flow across theoretical capillaries. The importance of surface tension, viscosity and pressure differential to flow (or leakage) of gases and liquids is theoretically presented. Leakage equations based on the laminar flow equations and utilizing a resistance factor (K_L) for leak paths are presented, and can be used to compare liquid and gas leakage across a given leak path.

Using the theoretical equations presented in the paper, some general observations are presented that explain why air leakage exceeds water leakage and why testing a product with water may not always find the product that leaks in a gas service.

About the Author

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Introduction

This article gives some practical and theoretical considerations that can be used in evaluating leakage. Laminar type leaks are discussed; especially the relationship that exists between gas and liquid leakage. From the information given, a comparative leakage analysis can be conducted on a laminar type leak path. Since a leakage path has no uniqueness as it relates to equipment, the concepts given in this article may be applied to leakage of valves, pumps, tanks, pressure vessels, etc. It is not the intention of this article to present a series of theoretical equations in which exact leakage rates across a leak path can be calculated, but to present a general method that can be used to predict or compare gas and liquid leakage across a leak path whose leak rate has been specified or has been established by some leakage method.

Definition

Leakage as used in this article is defined as flow per unit of time. Specifically, the leakage to be addressed is the type of flow that emanates from a leak path in a pressurized product that produces countable and/or measurable “drops” of liquid or “bubbles” of gas (when tested under water) over a measured period of time.

Volumetric changes to liquids do not appreciably change as they flow from a pressurized product through a leak path to the atmosphere. Due to compressibility of gases, large volumetric increases occur in gas flow as the pressure drops across the leak path; and very small leak rates are perceived as large because they are observed as “bubbles” at atmospheric conditions (14.7 psia @ ambient temperature). Since a unit of leaking gas from a pressurized product has its greatest natural volume at atmospheric conditions, the leakage observed is in its worst case condition.

Gas leakage, as used in this paper, is defined as the volume of gas that passes through a leak path, observed and measured at standard conditions (14.7 psia @ 60°F) over a measured period of time. See Figures 1A and 1B.

Theoretical

By theoretical methods we can set up common ground on which to discuss this leakage in drops and bubbles per unit of time and to establish the leakage rate occurring across a leakage path. Since the volume of a “drop of liquid” or a “bubble of gas” can be calculated, based on the assumption that they are spherical in nature, and time can be measured, leakage rates can be calculated. Table 1 gives the volume and leakage rates for various bubble or drop diameters when developing at various intervals of time.

From a practical standpoint, the diameter of a “drop” or “bubble” observed by an inspector (tester), operator or maintenance man of a piece of equipment is not known and really not important to the analysis presented herein. The usually mentioned “drops/minute” or “bubbles/minute” explanation of leakage with an estimated diameter is accurate enough as it relates to comparison of leakage given in this paper. Very close accuracy of the volumetric leak rates can be obtained by methods illustrated in Figures 1A and 1B. These leakage rates can be theoretically equated to “drop” or “bubble” diameter by correlating the drops or bubbles per minute to the volume collected over a measured length of time.

A theoretical review of some basics of fluid mechanics is required as we develop our basis for analyzing leakage. Any good text on fluid mechanics indicates that flow through pipe and capillaries can be characterized by one of the following flow modes:

Turbulent The flow stream is characterized by flow particles moving randomly in magnitude and direction in the flow stream. Turbulent flow exists for flow rates in conduits in which $Re > 4000$. Turbulent flow is the most common flow mode and normally occurs in piping systems designed to move fluids.

Laminar Sometimes known as streamline flow because particles of fluid move along the conduit in straight, parallel laminar layers. Laminar flow exists for flow rates in conduits in which $Re \sim 2000$. Laminar flow may occur in piping systems that move highly viscous fluids at low velocities.

Transition The flow stream is unpredictable in that either laminar or turbulent modes may exist. Transition flow occurs in a Reynolds number range of 2000–4000.

It can be shown that the leakage rate ranges that are addressed in Table 1 (countable drops or bubbles) include leaks that are in the *Laminar Flow Range*. This can be done by a comparison analysis of flow rates across theoretical capillaries that have fixed dimensions and can be theoretically analyzed, to those in Table 1 and showing that such flow rates have Reynolds numbers in the laminar flow region. Unlike capillaries, leak paths cannot be described by exact dimensions. Their dimensions and geometries are generally unknown. Even the flow direction and cross-section may vary across the leak path. There are no pure theoretical equations available to calculate flow rates across leak paths. Empirical methods must be used to show that the flow across a leak path is laminar. Modified theoretical equations may be used to predict the leakage rate across leak paths that have been experimentally evaluated. The treatment of flow through valves and other similar products, in the turbulent flow mode, and the modification of theoretical flow equation to include a flow resistance factor (K) will be used to support the use of a resistance factor (K_L) for laminar leak paths. Since the leak rates addressed in Table 1 parallel laminar flow across capillaries, the K_L resistance factor for leaks will be applied to the theoretical laminar flow equations.

Some well-known general equations* for flow through pipe or capillaries for the Turbulent and Laminar Flow Modes described above are needed to develop a theoretical position on leakage.

Turbulent Flow – Equation 1

$$h_L = \left(f \frac{L}{D} \right) \frac{v^2}{2g}$$

From the above equation, it can be noted that pipe or capillary friction have an influence on head or pressure loss during flow.

Turbulent Flow – Equation 2

$$h_L = K \left(\frac{v^2}{2g} \right)$$

This equation is equal to Equation 1 except that the (fL/D) term has been replaced by K. K is a resistance coefficient that can be experimentally determined for products such as valves, fittings, strainers, filters, etc. Once determined, this “K” factor can be used in Equation 2, or derivations thereof, to determine head loss (or pressure drop) for any fluid flow rate when the flow rate is in the turbulent flow mode (Re~4000). The equation, or derivation thereof, could also be used to apply the leakage rates across large leak paths where leakage rates are in the turbulent mode. Leak rates in the turbulent mode, however, are expected to greatly exceed those of countable “drops” and “bubbles” listed in Table 1. The equation is used here because a parallelism of applying a similar resistance coefficient (K_L) to leak paths in the laminar flow mode is suggested.

Laminar Flow – Equation 3

$$h_L = \left(\frac{64 L}{Re D} \right) \frac{v^2}{2g}$$

For laminar flow across a pipe or capillary, Equation 3 indicates that the friction factor is replaced by a function of the Reynolds number.

Equation 3 can be refined to specifically cover liquid and gas flow in the Laminar Flow Mode across pipe or capillaries, as follows:

Liquid Flow

Laminar Flow – Equation 3A

$$q_s = 169273 \left(\frac{\Delta P d^4}{\mu L_i} \right)$$

**See Appendix 1 for background of equations.*

Gas Flow

Laminar Flow – Equation 3B

$$q'_s = 11515 \left(\frac{\Delta P d^4}{\mu L_i} \right) P'_d$$

Since the Reynolds number is important to leak rate analysis, the general equations for Reynolds number are given as follows:

Reynolds Number – Equation 4

$$R_e = \frac{123.9 \rho v d}{\mu}$$

Liquid Flow – Equation 4A

$$R_e = 13.14 \frac{\rho q_s}{d\mu}$$

Gas Flow – Equation 4B

$$R_e = 1.004 \frac{q'_s S_g}{d\mu}$$

The above equations shall be used in flow calculations of capillaries to show that the flow rates noted in Table 1 lead to Reynolds numbers in the Laminar Flow Range.

The viscosity of the flowing fluid is also important in laminar flow analysis. Tables 2, 3 and 4 list viscosities of many common liquids and gases.

**Example 1 –
Water/Air Flow Comparison**

From Equation 3A, we can calculate the flow rate of water at 100 psig @ 60°F across a .002" diameter capillary, 1" long, as follows:

$$q_s = 169273 \left(\frac{\Delta P d^4}{\mu L_i} \right)$$

$$q_s = 169273 \left(\frac{100 \times (.002)^4}{1.13 \times 1.00} \right)$$

$$q_s = 2.40 \times 10^{-4} \text{ in}^3/\text{sec}$$

which is the equivalent of approximately 16 drops per minute (1/8" diameter) from the capillary. See Table 1.

The Reynolds number for this flow rate can be calculated from Equation 4A, as follows:

$$R_e = \frac{13.14 q_s \rho}{d\mu} = \frac{13.14 \times 2.40 \times 10^{-4} \times 62.4}{.002 \times 1.13} = 87$$

Since $R_e = 87$ is less than 2000, the flow is laminar.

From Equation 3B, we can calculate the flow rate of air at 100 psig @ 50°F across the same .002" diameter capillary, 1" long, as follows:

$$q'_s = 11515 \left(\frac{\Delta P d^4}{\mu L_i} \right) P'_a$$

$$q'_s = 11515 \left(\frac{100 \times (.002)^4}{.018 \times 1.00} \right)$$

$$q'_s = 5.88 \times 10^{-2} \text{ scis}^*$$

which greatly exceeds any of the bubble rates noted in Table 1. In fact, the bubble rate of this leak would not be countable, forming the equivalent of 3448 – 1/8" bubbles per minute.

The Reynolds number for this flow rate can be calculated from Equation 4B, as follows:

$$R_e = \frac{1.004 q'_s S_g}{d \mu}$$

$$R_e = \frac{1.004 \times 5.88 \times 10^{-2} \times 1.00}{.002 \times .018} = 1641$$

which is less than 2000 and is in the laminar range. Comparison of the two calculations leads to the first obvious conclusion:

The flow of air @ 60°F versus that of water @ 60°F across the same capillary at the same pressure drop is greatly different. In fact, Equations 3A and 3B can be equated to show that 60°F water flow across the same capillary at an equal pressure drop can be generalized as follows:

Air/Water Flow Comparison – Equation 5

$$q'_s = 4.27 P'_a \times q_s$$

This equation indicates air flow measured in bubbles passing through a capillary would be 245 times greater than water in equivalent size drops passing through the same capillary when both are at a pressure of 100 psig. The difference between air and water flow across a capillary becomes even greater as the pressure drop and average pressure increase.

Example 2 – Air/Water Flow Comparison

To make a further comparison of air/water flow, the flow across a 1" long capillary that is flowing 500 psig air @ 60°F at 8.5 x 10⁻⁵ scis (or 1 1/8" diameter bubble every 12 sec) is compared with water flow at the same conditions. See Table 1. What is the likelihood that this capillary would flow water?

This calculation requires the arrangement of Equation 3B to read as follows:

$$d^4 = \frac{q'_s \mu L_i}{11515 \Delta P P'_a}$$

* Standard cubic inch/second = scis.

From this equation, the diameter of the capillary that will permit air flow at the above rate can be calculated, as follows:

$$d^4 = \frac{8.5 \times 10^{-5} \times .018 \times 1}{11515 \times 500 \times 515/2}$$

$$d = 1.79 \times 10^{-4} \text{ inch}$$

Now that the diameter that will flow this small volume of air has been calculated, calculate the volume of water at the same conditions (500 psig @ 60°F) that will flow across the same capillary:

From Equation 3A:

$$q'_s = 169273 \left(\frac{\Delta P d^4}{\mu L_i} \right)$$

$$q'_s = 169273 \left(\frac{500 \times (1.79 \times 10^{-4})^4}{1.13 \times 1} \right)$$

$$q'_s = 7.69 \times 10^{-8} \text{ in}^3/\text{sec}$$

At this low flow, it would require 3.69 hours for the equivalent of 1 drop (1/8" diameter) of water to pass through the capillary. From a practical standpoint, this water flow would never be detected by visual means. One bubble of air flow every 12 seconds is expected to be visually detectable and illustrates the advantage of using air as a test medium in lieu of water.

Surface Tension – Capillary Flow

It has been suggested that surface tension may be the reason for the tremendous difference in air flow versus water flow across capillaries. Surface tension of water flow through a capillary with a round flow cross-section venting to the atmosphere can be calculated by use of the following general formula:

Surface Tension – Equation 6

$$P = \frac{4\sigma}{D}$$

This formula clearly indicates that as the diameter of the capillary decreases, the pressure to overcome the surface tension increases. If the pressure drop across the capillary is greater than the surface tension, flow is expected to take place. Note that the length of the capillary would not affect this calculation, only the diameter of the capillary in which the liquid is flowing. The surface tension σ for a number of liquids is shown in Table 5. Equation 6 can be applied to water flow for the capillary in Example 2 above, as follows:

$$P = \frac{4 \times .00504}{1.79 \times 10^{-4}} \left(\frac{1}{144} \right) = 9.38 \text{ PSI}$$

This calculation indicates that 9.38 psi is required to overcome the surface tension in the 1.79×10^{-4} " capillary. For pressure drops less than 9.38 psi, surface tension would not allow water flow to occur. For high pressure drops, it can be concluded that the main reason that water flow is retarded across the 1.79×10^{-4} " capillary more so than air is because of the high viscosity of water relative to air and not

because of surface tension. Surface tension would not stop a flow of water at 500 psig, as the above calculation indicates.

For surface tension to play a significant role in the flow of 60°F water at high pressure across a capillary, the diameter of the capillary needs to be in the 1×10^{-6} inch range, as illustrated by the following calculation:

$$P = \frac{4\sigma}{D}$$

$$P = \frac{4 \times .00504}{.000001"/12} \left(\frac{1}{144} \right) = 1680 \text{ PSI}$$

$$P = 1680 \text{ PSI}$$

This calculation indicates that a pressure drop of 1680 psig would be required just to overcome the effects of surface tension.

Laminar Flow Range/Capillaries

It can be established that the leak rates illustrated in Table 1 for 60°F water are in the Laminar Flow Range as long as the following ratio calculated from Equation 4A for Re 2000 is satisfied:

Flow/Capillary Diameter Ratio (Water) – Equation 4C

$$\frac{q_s}{d} \leq 2.76$$

Likewise, Equation 4B can be used to show that the leak rates illustrated in Table 1 for 60°F air are in the Laminar Flow Range, as long as the following ratio is satisfied:

Flow Capillary Diameter Ratio (Air) – Equation 4D

$$\frac{q'_s}{d} \leq 35.85$$

As long as the above ratios are met, 60°F water and air flow in capillaries are in the laminar flow mode. If the ratios are exceeded, the flow mode will be in the transition or turbulent flow modes.

Leakage Mechanics

Moving away from theoretical analysis of capillary flow but making a modification of those equations to apply to leak paths seems logical.

Since leak paths, areas, geometries, flow cross-sections and diameters vary, the laminar flow equations for capillary flow cannot be used to calculate leakage. The modification of Equation 1 to Equation 2 typically for valves for turbulent flow, suggests that a similar approach for flow across laminar flow leak paths can be used. The experimentally determined resistance factor (K) for valves with varying flow path geometries and characteristics paralleling what might be expected in leak paths has been used for many years to determine flow and/or pressure drop for valves.

In general, leakage rates in the following range are expected to represent *Laminar Type* leaks:

$$1 \times 10^{-2} \text{ in}^3/\text{sec} \text{ to } 1 \times 10^{-7} \text{ in}^3/\text{sec}$$

But unlike capillaries, leak paths do not have any easy ratio like Equation 4C and 4D to verify if laminar flow exists, since a Reynolds number calculation is impossible with a variable d dimension. Another method must be used to determine if laminar flow exists across leak paths.

As was done with Equations 1 and 2, those variables in Equations 3A and 3B, characteristic of the leak path, can be combined into a leak path resistance factor. By doing so, some common equations evolve that offer some hope of calculating or comparing leakage of gas and liquids across a leak path.

From Equation 3A for liquid flow across a capillary, the equation is modified for leakage as follows:

Equation 7

$$q_s = 169273 \left(\frac{d^4}{L_i} \right) \frac{\Delta P}{\mu}$$

Let $K_L = \left(\frac{d^4}{L_i} \right)$ where K_L is the resistance factor for a leak path.

$$q_s = 169273 K_L \frac{\Delta P}{\mu}$$

where Q_L and μ_L have been subscripted to denote liquid leakage and leaking liquid viscosity, respectively.

Equation 7 indicates that liquid leakage across a leak path is directly proportional to the pressure drop (ΔP) and inversely proportional to the viscosity (μ_L).

Similarly, Equation 3B for gas flow across a capillary, can be modified, as follows:

Equation 8

$$q'_s = 11515 \left(\frac{d^4}{L_i} \right) \frac{\Delta P P'_a}{\mu}$$

Let $K_L = \left(\frac{d^4}{L_i} \right)$ the same factor as in Equation 7, above

or

$$Q_g = 11515 \frac{K_L \Delta P P'_a}{\mu_g}$$

where Q_g and μ_g have been subscripted to denote gas leakage and leaking gas viscosity, respectively.

Equation 8 indicates gas leakage to be a function of the product of pressure drop (ΔP) and average pressure (P'_a) across the leak path and inversely proportional to viscosity (μ_g).

To determine if laminar flow exists across a leak path for gas leakage, a plot of experimentally determined leak rate (y axis) versus pressure drop (x axis) on log/log graph paper would suggest that laminar flow exists if the slope of the curve equals to 2. This can be equated from Equation 8, which indicates laminar flow gas leak rate is proportional to ΔP^2 , which is equivalent to the $(\Delta P \cdot P'_a)$ factor.

A logarithmic conversion of the equation would show that the slope of 2 could be expected. Likewise for liquid leakage, Equation 7 would indicate that a leak rate/pressure drop plot on log/log graph paper would have a slope of 1.

Equations 7 and 8 suggest that if a leakage rate for a leak path can be determined for a liquid or gas having a known viscosity and pressure drop, a resistance factor (K_L) can be determined for the leak path. This K_L factor can be used in Equations 7 or 8 to predict or compare the leakage across the same leak path at different pressure drops, or for a different type liquid and/or gas. Clearly, viscosity of the leaking fluid is the principal factor to be considered when comparing leakage rates. A comparison of gas to liquid leakage across the same leak path can be equated from Equations 7 and 8, as follows:

$$\frac{Q_g}{Q_L} = \frac{11515 K_L \frac{\Delta P_g P'_a}{\mu_g}}{169273 K_L \frac{\Delta P_L}{\mu_L}}$$

or

Comparative Gas/Liquid Leakage – Equation 9

$$\frac{Q_g}{Q_L} = .068 P'_a \left(\frac{\mu_L}{\mu_g} \right) \left(\frac{\Delta P_g}{\Delta P_L} \right)$$

where P'_a is average absolute pressure across the gas leak path and ΔP_g and ΔP_L have been subscripted to denote pressure drop across the gas leak path and liquid leak path, respectively.

For the special case where the pressure drop across the leak path for gas and liquid is equal, Equation 9 can be further simplified, as follows:

Comparative Gas/Liquid Leakage – Equation 9A

$$\frac{Q_g}{Q_L} = .068 P'_a \left(\frac{\mu_L}{\mu_g} \right)$$

Not readily evident by this equation is that the leakage of air across a given leak path is several orders of magnitude greater than water because of its lower viscosity and expansion characteristic. As an example, the comparative leakage of 1000 psig air @ 60°F versus 1000 psig water @ 60°F across the same leakage path can be calculated from Equation 9A, as follows:

$$Q_g = .068 P'_a \frac{\mu_L}{\mu_g} Q_L$$

$$Q_g = .068 \times \frac{1015}{2} \times \frac{1.13}{.018}$$

$$Q_g = 2166 Q_L$$

meaning that air would leak at a rate of 2166 times greater than water at the stated conditions.

Equation 9 also indicates that a 46 psig air test would be just as effective as a 6000 psig water test in determining leakage across the same leak path, calculated as follows:

$$\frac{Q_g}{Q_L} = .068 P'_a \left(\frac{\mu_L}{\mu_g} \right) \left(\frac{\Delta P_g}{\Delta P_L} \right)$$

meaning that 46 psig air would leak at the same rate as 6000 psig water across the same leak path.

Surface Tension/Leak Paths

The effect of surface tension on leak paths is probably greater than on capillaries because many leak paths have a slit cross-section. The pressure to overcome surface tension can be two to three times greater for leak paths that have a slit cross-section than a capillary with its round cross-section.

The comparative pressure to overcome surface tension in a slit leak path versus a capillary with the same cross-sectional area can be equated as follows:

Equation 10

$$P_s = .577 \sqrt{R} P_c$$

where

P_s = Surface Tension Pressure (Slit)

R = Ratio of Length/Width of Slit

P_c = Surface Tension Pressure (Capillary)

Some information suggests that no visible water leak when dry air at the same pressure will leak at the rate of 1.00×10^{-4} in³/sec, probably due to surface tension.

As the above calculations on capillaries indicate, it may not be due to surface tension but more due to the viscosity of water.

Vogt's own testing has discovered leaks that leak during high pressure (500 psig and 2000 psig) air testing in the 1.7×10^{-2} to 7.4×10^{-2} scis but will not pass water in any reasonable time period. These leaks, once tested with water, become plugged, probably due to surface tension or capillary action, and will not leak air until the water is driven from the leak path by a high-temperature furnace soak. This points up a disadvantage to testing with water prior to testing with air. Small leaks may become clogged with water and not leak on air test.

There is another gas leak flow method that is not addressed in this paper. This gas flow is known as Molecular Flow. Molecular flow across a leak path occurs by individual molecules and can be detected only by sophisticated electronic leak detection equipment such as a helium mass spectrometer. Such a small leak would be so small that "bubble" formation would not occur. Molecular flow is proportional to the ΔP across the leak path and inversely proportional to the square root of the leaking gas molecular weight, as follows:

$$Q_g \propto \frac{\Delta P}{\sqrt{m}}$$

The perception that the molecular weight (m) of a gas is the property most influencing leakage across a leak path applies to molecular leakage flow. As Equation 8 indicates, the critical gas property that

has the greatest influence on laminar leakage is the gas’s viscosity. For visible “bubble” type leakage, viscosity is the gas property that we must evaluate. Molecular type leakage could be the subject of another paper.

General Observations

The equations given in this paper generally apply to leak paths whose characteristics are not affected by pressure. The physical dimensions of the leak path remain fixed and unaffected by pressure. Leaks are also equated on a volumetric basis.

It may be interesting to note that visible volumetric leaks expressed in weight flow terms would not be very impressive, as follows:

Typical Volumetric Leak*	Time for 1 Pound Air to Leak	Time for 1 Pound Water to Leak
1 x 10 ⁻⁶ scis	677 Years	9.9 Months
1 x 10 ⁻³ scis	8.4 Months	7.27 Hours

*See Table 1 for typical drops/bubble frequency.

Leak paths that have pressure induced characteristics will not follow the rules of laminar flow leakage. Some leak paths may act as check valves at low test pressures and open up at high pressure, permitting leakage. Other types of leak paths may clean themselves during pressurization and/or become enlarged as a result of pressurization. Such leak paths when plotted on graph paper will show a disparity to the laminar flow plot.

Pressure induced distortions of leak path geometry may throw off correlation of leak rates based on Equations 7 and 8.

Application of Equation 9A would show the big advantage of testing products with gas. Because of the low viscosity of gases versus liquids and because a leaking gas reveals itself at its greatest volume, gases are superior to liquids in leak detection work. The big disadvantage in using high pressure gas for testing is the increased danger of testing and is the primary reason gas test pressures above 100 psig are seldom specified or used in production testing.

Equations 7 and 8 indicate that liquid or gas pressure testing should be at the operating pressure or at maximum pressure differential (ΔP) the product is expected to see. This will increase sensitivity and locate leaks that have leak paths enhanced by pressure. For leak paths that are not enhanced or physically affected by pressure, a low pressure gas test may be more sensitive than a high pressure liquid test. Refer to Equation 9.

If a product cannot be leak tested at operating pressure, consideration should be given to testing with a low pressure gas to determine small leaks that will not pass a test fluid such as water.

Flowserve Vogt Valves has recognized the value of high pressure gas testing and has its own in-house supplemental high pressure gas test procedure used for valves that go in critical service or where a history of leakage has occurred in valves that have historically passed the Industry Standard test.

Leak detection is time sensitive. Leaks that may rapidly be detectable during gas testing may not have time to develop when testing with a liquid such as water.

Most valve industry standards require testing with water and/or air. The high pressure shell testing is limited to water, or a fluid having a viscosity equal to or less than water. The closure testing of gate valves requires an 80–100 psig air test.

Review of Tables 2 and 3 would indicate that water and air are very good choices as test fluids because of their viscosity. Few liquids have a lower viscosity than water. Those that do would have economical and safety constraints limiting their use. Air is an economical choice as well.

Kerosene has also been used for many years as a testing medium because of its lubricating quality. A review of Equation 7 and viscosity Table 3 indicates that a leak path would leak twice as much water as kerosene in a given period of time. Table 5 would indicate a preference for kerosene over water if surface tension is considered.

Surface tension pressure (Equation 6) is a measure of a flow or leak path capillarity. The higher the surface tension pressure, the greater the leak path capability to draw in water and plug itself. Once plugged with water, a gas such as air is not expected to pass through the leak path unless it exceeds the surface tension pressure. Air testing when used to determine very small leaks should precede water testing.

As noted from Table 2, the viscosities of several gases normally used in testing—air, nitrogen and helium—are very similar. Therefore, a change in test gas will not markedly improve the sensitivity of leak detection using gas-under-water techniques.

Flowserve Vogt valves are tested to meet industry standards *MSS-SP-61* and/or *API-598*. Both of these specs require high pressure testing of the shell. Normally, water is used as the test fluid for safety reasons. Both of these standards give a good test, yet if a valve goes into a high pressure dry gas or steam service, the valve could still have a small leak not detectable during the water testing. The perception of the user is that the valve was not tested, but in reality, the lower viscosity of gases (Table 2) and steam (Table 4) pass through a leak path much more rapidly than water, as projected by Equations 9 or 9A.

The two industry standards noted above require that products be shell tested with water at a pressure 1.5 times the 100°F valve rating. In addition to leak tightness, this test would also verify the structural integrity of the product. Safety considerations do not permit the testing of many of these valves with a gas test to the 1.5 x 100°F valve rating requirement.

A review of Table 3 would indicate which liquids leak the greatest, as predicted by Equation 7. The smaller the viscosity of a liquid, the greater the leakage. A typical comparison would indicate that ammonia liquid would leak at a rate approximately ten times greater than water.

A review of Tables 2 and 4 and Equation 8 indicates which gases and vapors leak the greatest, as predicted by Equation 8. The smaller the viscosity of a gas, the greater the leakage. A typical comparison would indicate that hydrogen gas would leak at a rate approximately twice as great as air.

A review of Tables 2, 3 and 4 and Equation 9A indicates that almost all gases, including steam, leak at a greater rate than does water.

Because the viscosity of liquids decreases with increasing temperature, a product that has been tested with water at ambient temperature may leak if placed in similar service at a higher temperature. Example: A valve tested with 78°F water and placed in saturated water service may leak due to the difference in viscosity. Refer to Equation 7 and viscosity Table 3.

The viscosity of gas and vapors, including steam, increase with increasing temperature and, therefore, their tendency to leak decreases with increasing temperature.

Increasing the gas test ΔP across a leak path by a factor of 5 (100 psig to 500 psig) will increase the leakage rate by a factor of 25. Increasing the pressure across the leak path is the simplest method to improve leakage detection sensitivity. Refer to Equation 8.

Increasing the water test ΔP across a leak path by a factor of 5 (500 psig to 2500 psig), unlike gas testing, only increases the liquid leakage by a factor of 5. Refer to Equation 7.

If a detected gas leak is in the laminar flow range, extrapolation to higher internal pressures using the relationship $Q_g \propto \Delta P^2$ may be carried out.

It is generally believed that leak paths that leak air at a rate less than 1×10^{-5} scis will not pass water. Flowserve Vogt's testing confirms this, but we have also experienced much larger leaks of air that will not pass water over any reasonable period of time.

Vogt has recorded water leaks at 2 cc/hr. (3.4×10^{-5} in³/sec) during extended test periods. Water leaks smaller than this are seldom ever observed and/or recorded, indicating that such a water leak is at the threshold of detectability or occurrence.

Figure 1A

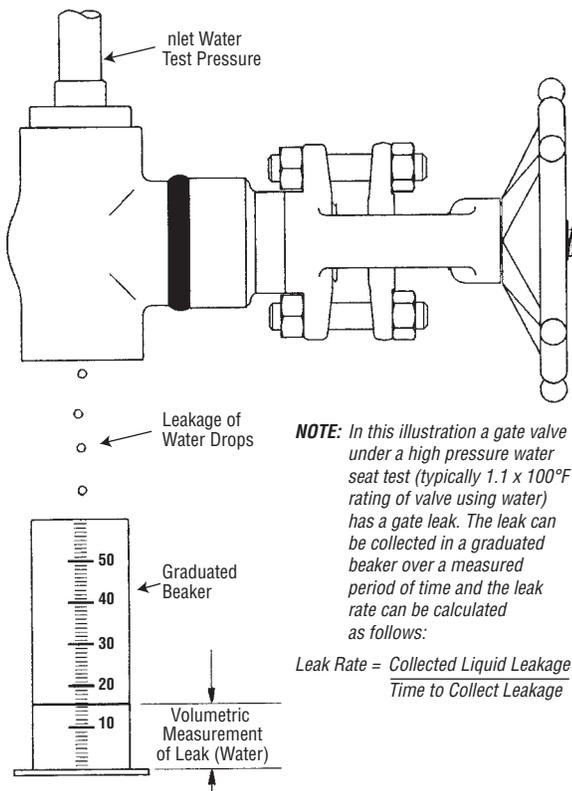
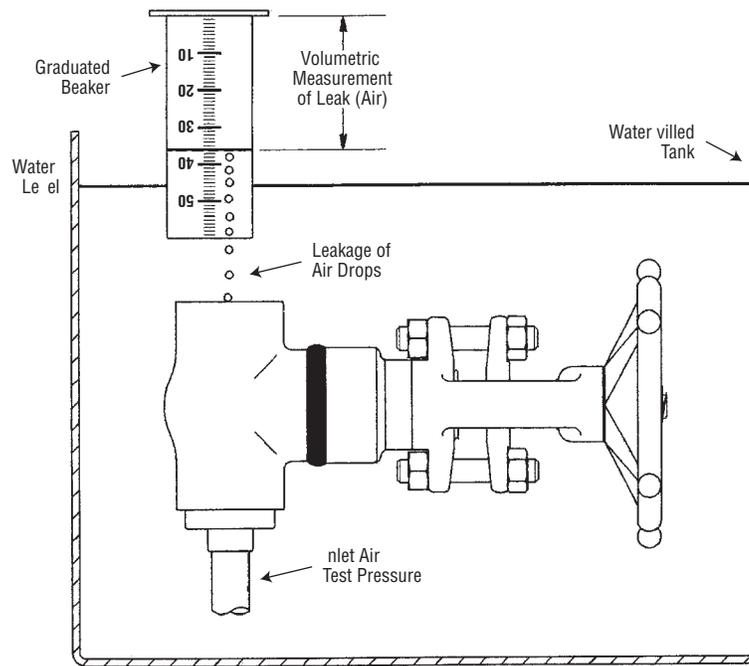


Figure 1B



NOTE: In this illustration a gate valve under a low pressure gas-under-water seat test (typically 100 psig air) has a gate leak. To collect the leak, the graduated beaker is initially filled with water, and the beaker inlet is kept below the surface of the water of the tank. The bubbles of leakage are collected in the beaker, which displaces the water, as illustrated. The displaced water represents the volume of the gas leakage. The pressure of the collected gas is basically at 14.7 psia or atmospheric pressure. The leak is collected over a measured period of time and the leak rate can be calculated as follows:

$$\text{Leak Rate} = \frac{\text{Collected Volume of Gas (Std. Conditions)}}{\text{Time to Collect Gas Leakage}}$$

Table 1

Drop or Bubble Diameter	Volume ⁽¹⁾ Drop/Bubble	Leak Rate (scis) ^{(2) (3)}										
		Drops/Bubbles per Minute										
in.	In ³	4	5	6	8	10	16	20	25	32	50	64
1/2"	1.598 x 10 ⁻⁵	1.06 x 10 ⁻⁶	1.33 x 10 ⁻⁶	1.59 x 10 ⁻⁶	2.13 x 10 ⁻⁶	2.66 x 10 ⁻⁶	4.26 x 10 ⁻⁶	5.33 x 10 ⁻⁶	6.65 x 10 ⁻⁶	8.52 x 10 ⁻⁶	1.33 x 10 ⁻⁵	1.70 x 10 ⁻⁵
1/4"	1.278 x 10 ⁻⁴	8.52 x 10 ⁻⁶	1.06 x 10 ⁻⁵	1.28 x 10 ⁻⁵	1.70 x 10 ⁻⁵	2.12 x 10 ⁻⁵	3.41 x 10 ⁻⁵	4.24 x 10 ⁻⁵	5.30 x 10 ⁻⁵	6.82 x 10 ⁻⁵	1.06 x 10 ⁻⁴	13.64 x 10 ⁻⁴
3/32"	4.314 x 10 ⁻⁴	2.88 x 10 ⁻⁵	3.60 x 10 ⁻⁵	4.32 x 10 ⁻⁵	5.76 x 10 ⁻⁵	7.20 x 10 ⁻⁵	1.15 x 10 ⁻⁴	1.44 x 10 ⁻⁴	1.80 x 10 ⁻⁴	2.30 x 10 ⁻⁴	3.60 x 10 ⁻⁴	4.60 x 10 ⁻⁴
1/8"	1.023 x 10 ⁻³	6.82 x 10 ⁻⁵	8.52 x 10 ⁻⁵	1.02 x 10 ⁻⁴	1.36 x 10 ⁻⁴	1.71 x 10 ⁻⁴	2.73 x 10 ⁻⁴	3.42 x 10 ⁻⁴	4.26 x 10 ⁻⁴	5.45 x 10 ⁻⁴	8.52 x 10 ⁻⁴	1.09 x 10 ⁻³
5/32"	1.997 x 10 ⁻³	1.33 x 10 ⁻⁴	1.66 x 10 ⁻⁴	2.00 x 10 ⁻⁴	2.66 x 10 ⁻⁴	3.33 x 10 ⁻⁴	5.32 x 10 ⁻⁴	6.66 x 10 ⁻⁴	8.30 x 10 ⁻⁴	1.06 x 10 ⁻³	1.66 x 10 ⁻³	2.12 x 10 ⁻³
3/16"	3.451 x 10 ⁻³	2.30 x 10 ⁻⁴	2.88 x 10 ⁻⁴	3.45 x 10 ⁻⁴	4.6 x 10 ⁻⁴	5.75 x 10 ⁻⁴	9.2 x 10 ⁻⁴	1.15 x 10 ⁻³	1.44 x 10 ⁻³	1.84 x 10 ⁻³	2.88 x 10 ⁻³	3.68 x 10 ⁻³

1) Volume of drop or bubble = π/6 (diameter)³

2) Standard Cubic Inch per Second Leakage.

$$\text{Leakage Rate (scis)} = \left(\frac{\text{No. Drops or Bubbles}}{\text{minute}} \right) \times \left(\frac{\text{Vol. Drop/Bubble (in}^3\text{)}}{1} \right) \times \left(\frac{\text{minute}}{60 \text{ sec}} \right)$$

3) Standard in scis refers to the collection of bubbles in gas-under-water type tests in which the visible bubble is observed or collected at standard conditions – 14.7 psia @ 60°F.

Since the volume of a leaking liquid does not change across a leak path, the leak rates noted above are equal to in³/sec when referring to liquid leakage rates.

Table 2: Viscosity of Gases and Vapors (at Atmospheric Pressure)

Gas/Vapor	Viscosity (Centipoise)	Temp. °F
Acetylene	.010	70
Ammonia	.010	70
Argon	.021	32
Benzene	.009	177
Butane	.008	70
Carbon Dioxide	.015	70
Carbon Monoxide	.014	70
Chlorine	.013	70
Chloroform	.011	143
Dowtherm A	.0092	400
Dowtherm E	.0012	400
Ethane	.010	70
Ethylene	.010	70
Freon 11	.010	70
Freon 12	.013	70
Freon 113	.013	80
Freon 114	.015	80
Helium	.020	70
Hydrogen	.009	70
Hydrogen Chloride	.014	32
Hydrogen Sulfide	.012	32
Methane	.011	70
Neon	.030	32
Nitrogen	.018	70
Propane	.008	32
Oxygen	.020	70
Sulfur Dioxide	.013	70
Water Vapor	.013	212

Viscosity of Air (at Atmospheric Pressure – In Centipoise)

Temp. °F	Viscosity (Centipoise)
0	.016
40	.017
60	.018
100	.019
120	.020

NOTE: The viscosity of gases increases with increasing temperature and is negligently affected by pressure except at extremely high pressures.

Table 3: Viscosity of Liquids (at Atmospheric Pressure)

Liquid	Viscosity (Centipoise)	Temp. °F
Acetic Acid	1.04	86
Alcohol-Allyl	1.17	86
Alcohol-Ethyl	1.20	86
Alcohol-Isopropyl	2.00	80
Alcohol-Methyl	.60	86
Ammonia	.10	80
Benzene	.65	70
	.50	100
Benzol	.57	86
Brine, CaCl (20% Salt)	2.30	70
	1.30	100
Brine, NaCl (20% Salt)	2.00	70
	1.40	100
Bromide	.91	86
Butane	.18	60
Butyric Acid	1.30	86
Carbon Disulfide	.35	86
Carbon Tetrachloride	.97	70
	.74	100
	.85	86
Chlorine Trifluoride	.41	77
Chloroform	.52	86
Dowtherm A	2.60	100
Dowtherm A	.38	400
Dowtherm E	1.05	100
Dowtherm E	.27	400
Ethane	.05	60
Ethyl Bromide	.37	86
Ethyl Ether	.22	86
Ethylene Bromide	1.48	86
Ethylene Chloride	.74	86
Ethylene Glycol	19.90	68
Formic Acid	1.46	86
Freon 11	.42	80
Freon 12	.26	80
Freon 113	.65	80
Freon 114	.37	80
Gasoline (SIG. 0.68)	.28	70
Glycerol	207.00	68
Glycerine	830.00	68.54
Heptane	.38	86
Hexane	.30	86
Hydrazine	.90	77

Liquid	Viscosity (Centipoise)	Temp. °F
Kerosene	2.10	60
	1.90	77
Linseed Oil	3.10	86
Mercury	1.50	80
Methyl Chloride	.25	80
Methyl Iodine	.46	86
Nitrogen Tetraoxide	.34	100
Oxtane	.48	86
Pentame	.22	86
Propane	.15	60
Propionic Acid	.96	86
Propyl Alcohol	1.78	86
RP-1 Fuel	1.17	100
SAE 10 Lube Oil	2.00	60
SAE 30 Lube Oil	450.00	60
Sodium Hydroxide (20%)	3.50	80
Sulfuric Acid (20%)	1.30	80
Toluene	.52	86
Tupentine	1.27	86
	1.80	32
	1.55	40
	1.31	50
	1.13	60
	.98	70
	.86	80
	.80	86
	.68	100
	.56	120
	.43	150
	.31	200
	.28*	212
	.19*	300
	.14*	400
.095*	500	
.065*	600	
Water		

1) The viscosity of liquids decreases with increasing temperatures.

2) The viscosity of liquids is negligently affected by pressure except at extremely high pressures.

*At Saturated Pressure.

Table 4: Viscosity of Steam

Pressure (psig)	Temp. °F	Viscosity (Centipoise)
Saturated ⁽¹⁾		
0	212	.014
100	338	.017
400	448	.021
600	488	.024
800	520	.027
1200	569	.032
Superheated ⁽²⁾		
100	800	.025
100	1000	.028
400	800	.027
400	1000	.030
600	800	.028
600	1000	.031
800	800	.029
800	1000	.032
1200	800	.032
1200	1000	.034

1) Viscosity of Saturated Steam increases with increasing pressure and temperature.

2) Viscosity of Superheated Steam at pressure less than 800 psig increases with increased superheat.

Table 5: Surface Tension of Liquids in Contact with Air (at 1 Atmosphere Pressure In lb/ft)

Liquid	Temp. °F	Surface Tension (in Air) lb/ft
Alcohol, Ethyl	68	.00153
Benzene	68	.00198
Carbon Tetrachloride	68	.00183
Crude Oil	68	.00200
Dowtherm A	68	.00275
Dowtherm E	68	.00254
Gasoline (SG* = 0.68)	68	.0013 – .0016
Glycerin	68	.00435
Hexane	68	.00126
Kerosene (SG* = 0.907)	68	.00260
Mercury	68	.03280
Octane	68	.00149
Oil, Machine (SG* = 0.907)	68	.00260
SAE 10 Oil	68	.00240
SAE 30 Oil	68	.00500
Salt Water	68	.00504
Water	32	.00518
	40	.00514
	50	.00508
	60	.00504
	70	.00497
	80	.00492
	100	.00479
	120	.00466

NOTE: Surface tension decreases slightly with increasing temperatures.

*SG = Specific Gravity

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Appendix 1 Source of Equations in Paper

Nomenclature

(The following symbols are used in this appendix only. For other nomenclature, see inside front cover.)

- A = Cross sectional are of pipe/capillary, in square feet
- P₁ & P₂ = Inlet/Outlet pressure, in pounds per square inch absolute.
- P_S = Surface Tension Pressure for slit flow path, in pounds per square foot.
- P_C = Surface Tension Pressure for Capillary, in pounds per square foot.
- q₁ = Rate of Flow, in cubic feet per second at inlet conditions.
- q₂ = Rate of Flow, in cubic feet per second at outlet conditions.
- V₁ = Specific Volume of fluid, in cubic feet per pound.
- W = Rate of Flow, in pounds per hour.
- w = Rate of Flow, in pounds per second.
- μ_e = Absolute (Dynamic) Viscosity, in pounds mass per foot second.

Equation 1

Darcy Equation

(Head Loss through Straight Pipe – Turbulent Flow)

$$h_L = \left(f \frac{L}{D} \right) \frac{V^2}{2g}$$

Equation 2

Modified Darcy Equation

(Head Loss through Valves – Turbulent Flow)

$$h_L = (K) \frac{V^2}{2g}$$

Equation 3

Darcy Equation – Laminar Flow

(Head Loss through Straight Pipe or Capillaries – Laminar Liquid Flow)

$$h_L = \left(\frac{R_e}{64} \right) \left(\frac{L}{D} \right) \left(\frac{V^2}{2g} \right)$$

$$\text{Since } R_e = \frac{\rho V D}{\mu_e}, \quad h_L = \frac{114 \Delta P}{\rho},$$

$$\mu_e = \frac{\mu}{1487}, \quad D = \frac{d}{12} \quad \text{and} \quad \frac{L_i}{12} = L$$

Equation 3 can be converted to Equation 3A, as follows:

$$q_s = 169273 \left(\frac{\Delta P d^4}{\mu L_i} \right)$$

Equation 3B is derived for laminar gas flow across straight pipe, starting with the following equation and assumptions:

Simplified Compressible Flow – Gas Pipeline Flow

$$w^2 = \left[\frac{144g DA^2}{\bar{V}_1 f L} \right] \left[\frac{(P'_1)^2 - (P'_2)^2}{P'_1} \right]$$

1. Isothermal flow exists.
2. No mechanical work is done on or by the system.
3. Steady flow exists.
4. The flowing gas obeys the gas laws.
5. The velocity may be represented by the average velocity of a cross-section.
6. The friction factor is represented by $64/Re$ since laminar flow exists.
7. The pipeline is long (compared to diameter) and straight between end points.
8. Flow acceleration can be neglected because the pipeline is long compared to diameter.

Since $\frac{(P'_1)^2 - (P'_2)^2}{P'_1} = \frac{2 \Delta P P'_a}{P'_1}$

and $Re = \frac{6.31W}{d\mu}$ or $Re = \frac{.00175 w}{d\mu}$,

$$v = \frac{183.3 q_1}{d^2}$$

$$P'_1 q_1 = P'_2 q_2, \quad v = \frac{183.3 w \bar{V}_1}{d^2},$$

$$\frac{L_i}{12} = L \quad \& \quad \frac{d}{12} = D$$

Equation 3B can be derived as follows:

$$q'_s = 11515 \left(\frac{\Delta P d^4}{\mu L_i} \right) P'_a$$

Equation 4

Reynolds Number Equation – General

$$\text{Since } Re = \frac{\rho v D}{\mu_e}, \mu_e = \frac{\mu}{1487} \text{ \& } D = \frac{d}{12}$$

Equation 4 can be derived as follows:

$$Re = \frac{123.9 \rho v d}{\mu}$$

$$\text{Since } v = \frac{q_s}{12A} = \frac{4 q_s}{12\pi d^2}$$

Equation 4 can be converted to **Equation 4A** as follows:

$$Re = \frac{13.14 \rho q_s}{d\mu}$$

$$\text{From } Re = \frac{482 q'_h S_g}{d\mu}$$

$$\text{Since } q'_s = \frac{1728 q'_h}{3600}$$

Equation 4B can be derived as follows:

$$Re = \frac{1.004 q'_s S_g}{d\mu}$$

$$\text{Since } Re = \frac{13.14 \rho q_s}{d\mu} \text{ from Equation 4A}$$

Let $Re \leq 2000$ (laminar flow), $\ell = 6.24 \text{ lb/ft}^3$, and $\mu = 1.13$ (for water).

Equation 4C can be derived as follows:

$$\frac{q_s}{d} \leq 2.76$$

$$\text{Since } Re = \frac{1.004 q'_s S_g}{d\mu} \text{ from Equation 4B}$$

Let $Re \leq 2000$, $S_g = 1.00$ and $\mu = .018$ (for air).

Equation 4D can be derived as follows:

$$\frac{q'_s}{d} \leq 35.85$$

Ratio of q'_s to q_s from Equations 3B and 3A across same capillary, same ΔP , and same temperature.

Since $\mu = 0.18$ (air) and $\mu = 1.13$ (water) @ 60°F, Equation 5 can be determined.

Equation 5

$$q'_s = 4.27 P'_a \times q_s$$

Equations 7, 8, 9, and 9A are derived as illustrated in the paper.

Equation 6

General Surface Tension Equation – Round Capillary

$$P = \frac{4\sigma}{D}$$

Since $P_s = \frac{2\sigma}{w}$ for elongated leak path (slit) of width (w) and length (L).

$$\text{Let } L \times w = \frac{\pi}{4} d^2$$

Area Slit = Area Capillary

$$\text{and } R = \frac{L}{w}$$

Ratio of Length/Width of Slit

$$\text{then } P_s = \frac{2.309\sigma \sqrt{R}}{D}$$

$$\text{and since } P_c = \frac{4\sigma}{D}$$

$$\frac{P_c}{P_s} = .577 \sqrt{R}$$

which is Equation 10, as follows:

Equation 10

$$P_s = .577 \sqrt{R} P_c$$

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