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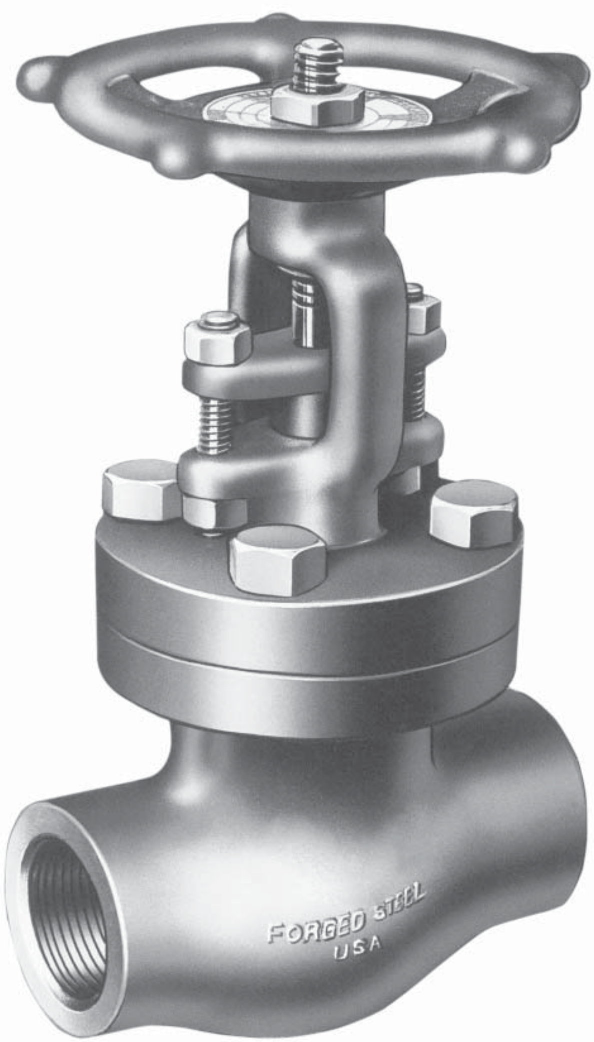
Fugitive Emissions
A Leakage Viewpoint

FCD VVABR1012-00 – 01/05 (Replaces CB-12)



Experience In Motion

Fugitive Emissions

A leakage viewpoint

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Abstract

Equipment fugitive emissions has created a new acronym: PPM(v) (parts per million, volumetric). This paper is an update of the author's earlier paper "A Treatise on Leakage" but specific to fugitive emissions and the PPM(v)s leakage acronym. The paper presents how PPM leakage can be correlated with traditional "bubbles" of leakage and how the basic laminar leakage equations can be applied to EPA's list of hazardous air pollutants to project comparative leakage using air and water leakage as the practical standard.

About the Author

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He is active in the American Society of Mechanical Engineers (ASME), the American Petroleum Institute (API), the Valve Manufacturers Association (VMA), and the Manufacturing Standardization Society of the Valve and Fitting Industry (MSS). He is a member of ASME B16 and B31 Main Committees and is Chair of ASME B16 Subcommittee F. He serves on API Refinery Subgroups on Gate Valves and Quality. He currently serves as president of MSS.

Background

In the author's paper, "A Treatise on Leakage," theoretical equations were developed that can be used to compare liquid and gas flow rates across leak paths in the laminar flow mode. The laminar flow mode was defined as flow in conduits in which the Reynolds Number (Re) ≤ 2000. It was shown that laminar flow can be characterized as flow that emanates from leak paths in "drops" or in "bubbles" of leakage. For convenience, the basic laminar leakage equations presented in "A Treatise on Leakage" are presented here as follows:

Equation 1: Liquid Flow Across Leak Path

$$Q_L = 169273\, K_L \frac{\Delta P}{\mu_L}$$

Equation 2: Gas Leakage Across Leak Path

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

Equation 3: Comparative Gas/Liquid Across Same Leak Path

$$\frac{Q_g}{Q_L} = .068\, P'_a \left(\frac{{}_L}{{}_g} \right)$$

Nomenclature

Various rates and sizes of "drops" and "bubbles" per minute were quantified in a leakage table, which is also included here for convenience.

Q_L	Leakage rate of liquid across a leak path, in cubic inches per second at flowing conditions.
Q_g	Leakage rate of gas across a leak path, in cubic inches per second at standard conditions (14.7 psia @ 60°F)
K_L	Resistance coefficient for leak path for use in laminar flow equation.
ΔP	Differential pressure across capillary/pipe or leak path, in psi.
P'_a	Average pressure across a leak path, in pounds per square inch absolute (psia).
M_U μ	Absolute (dynamic) viscosity, in centipoise.
μ_L	Viscosity of liquid in centipoise.
μ_g	Viscosity of gas in centipoise.

Fugitive Emissions

The purpose of this paper is to update the “A Treatise on Leakage” paper as it relates to leakage of the hazardous air pollutants (HAPS) and to correlate the fugitive emissions PPM(v) leakage rates to the traditional “bubbles” of leakage presented in the earlier paper.

Since the “A Treatise on Leakage” paper was published, the issue of fugitive emissions has emerged. Fugitive emissions in the context of this paper is defined as follows:

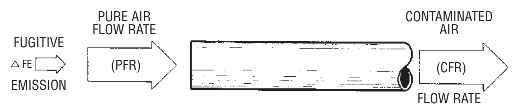
Fugitive emissions is the loss of VOCs (volatile organic compounds)* through sealing mechanisms separating process fluid from the environment. Fugitive emissions is also referred to as equipment leaks. The equipment includes pumps, valves, compressors, pressure relief devices, open-ended valves or lines, flanges, or connectors used within a processing plant.

In short, fugitive emissions is nothing more than equipment leakage of certain fluids, but a new term to report its intensity has emerged. This new term is PPM(v) — parts per million, volumetric.

Since it may not be readily evident from Equations 1, 2 and 3, the following leakage comparisons are summarized:

> Across any given leak path, the volumetric leakage rate of a gas will be much greater than for a liquid. This is due to the fact that the viscosity of gases is much less than that of liquids, and the compressibility of gases allows it to emanate from a leak path to the atmosphere at its greatest natural volume. Liquids, being incompressible, do not grow in volume as they move across a leak path to the atmosphere. Equations 1 and 2 indicate that the leakage rate is inversely proportional to the fluid viscosity. Since liquids have larger viscosities than gases, liquid flow leakage is projected to be less across a given leak path. Equation 2 indicates that a gas leakage across a given leak path is a function of $\Delta P \times P_a$, while leakage rate for a liquid from Equation 1 is a function of ΔP only. This pressure factor influence on leakage may not be evident but it emerges from the theoretical consideration that a gas under higher pressure entering and moving isothermally across a leak path will emerge at atmospheric pressure much greater than its starting volume, while an incompressible liquid leakage volume would not significantly increase upon emerging to the atmosphere.

Figure 1



ΔFE	Fugitive Emission Flow Rate – SCCM
PFR	Pure Air Flow Rate – SCCM
CFR	Contaminated Air Flow Rate – SCCM
CFR	PFR + ΔFE
SCCM	Standard Cubic Centimeters per Minute

What is the resultant theoretical PPM(v) of a CFR resulting from the introduction of a small volatile organic contaminant (VOC) ΔFE flow rate into a pure air flow (PFR) stream?

NOTE: A typical ΔFE is small compared to the PFR and can be dropped from the denominator of the following equation without making a significant result on the calculation.

$$\text{PPM} = \frac{\Delta\text{FE}}{\text{PFR}} \times \frac{10^6}{10^6}$$

$$\text{PPM} = \frac{\Delta\text{FE} \times 10^6}{\text{PFR}} \times \left(\frac{1}{10^6}\right)$$

$$\text{PPM} = \frac{\Delta\text{FE} \times 10^6}{\text{PFR}} \times \left(\frac{1}{\text{million}}\right) = \frac{\text{Parts contaminant per}}{\text{million}}$$

Typical Calculation

ΔFE = 1 SCCM

PFR = 2 liters/minute or 2000 SCC/minute

$$\text{PPMV} = \frac{1 \times 10^6\ \text{SCCM}}{2000\ \text{SCCM}} = 500$$

Water and air have been used for years as test fluids in the equipment industry for testing of products. From this longtime practice, flow from a leak path characterized as “drops” or “bubbles” per minute has been historically used to quantify leakage. Applying Equation 3 to an air verses water leakage calculation would clearly show that air with its lower viscosity would leak at a much greater volumetric rate than would water across the same leak path at the same ΔP. It can also be shown that an air test at a lower ΔP would show more leakage (bubbles) across the same

* *Volatile Organic Compound (VOC) is any compound containing the element carbon, excluding methane, carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, ammonium cabonate and exempt compounds. (From SCAQMD Rule 1173, amended 12/7/90.)*

leakage path than would water leakage (drops) at a higher ΔP water test.

Using water and air as benchmarks for leakage across leak paths, Equations I and 2 can be used to compare the relative leakage rates of a number of the hazardous air pollutants (HAPs). The Environmental Protection Agency (EPA) has a published listing of those compounds that are currently considered hazardous.

Table 2 represents the leakage rate multiplier determined from Equation 1 that could be used for a number of HAPs when in liquid state. Using water leakage as the base (1.00), Table 3 would indicate that benzene would leak at a rate 9.8 times greater than air across a given leak path at the same ΔP.

Table 3 represents the leakage rate multiplier determined from Equation 2 that can be used for a number of the HAPs when in gas/vapor state. Using air leakage as the base (1.00), Table 3 would indicate that benzene would leak at a rate 2.34 times greater than air across a given leak path at the same ΔP.

Table 4 is an extensive listing of the viscosities of many of the EPA-listed hazardous pollutants. These viscosities can be used with Equations 1, 2 or 3 to establish their relative intensity to leak verses other fluids in the table or the traditional test fluids with viscosities listed in Table 4a.

The PPM(v) leakage indicator has emerged as the most practical measurement method for fugitive emissions leakage. It has been promoted by organic vapor analysis (OVA) instruments that have been developed over the years that have the capability to continuously pump a sample of the atmosphere surrounding equipment through its internal analyzer to detect any trace of VOCs that get into that flow stream. The OVA instruments give the concentration of the VOC in the flow stream in terms of PPM(v) (parts per million, volumetric). Thus, fugitive emissions (equipment leakage) has a new term for leakage. But this PPM(v) leakage can be theoretically correlated with "bubbles" of leakage by calculating the PPM(v) concentration the "bubbles" of leakage from Table 1 would have it introduced into a typical flow stream of 2 liters/minute.

Table 1

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

(1) Volume of drop or bubble = $\frac{\pi}{6}(\text{diameter})^3$

(2) Standard Cubic Inch per Second Leakage

$$\text{Leakage Rate (SCIS)} = \left(\frac{\text{No. drops or bubbles}}{\text{minute}}\right) \times \left(\frac{\text{Vol. (drop/bubble) (in}^3\text{)}}{1}\right) \times \left(\frac{\text{minute}}{\text{60 sec.}}\right)$$

(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 in^3/sec when referring to liquid leakage rates.

Table 1A relates the correlation of PPM(v) fugitive emissions to bubbles of leakage. See Figure 1.

As an example, Table 1A indicates that if the volumetric flow rate equal to 6 bubbles/minute (⅛" bubble size) of pure methane is introduced into a 2 liters/minute flow stream and thoroughly mixed, a theoretical 50 PPM methane flow system would result. The highly used 10,000 PPM fugitive emissions standard for an equipment leak is so large that they are not illustrated in the table. This may mean the leak rate is so large that it is not in the laminar flow range. Other commonly used benchmarks of fugitive emissions leakage, 100 PPM and 500 PPM, can be correlated with “bubbles” of leakage in the table at various “bubbles” sizes.

The 100 PPM and 500 PPM fugitive emissions leakage standards are projected as laminar type leaks due to their correlation with “bubbles” of leakage in Table 1A.

Summary

This paper has presented the basic laminar flow leakage equations. From these equations, a comparative leakage propensity of several hazardous air pollutants can be determined. The data suggests that many of the HAPs with their low viscosity will be more difficult to contain than would air or water, traditionally used to pressure test equipment. The PPM(v) acronym for fugitive emissions has been correlated with traditional “bubbles” of leakage in a table that would suggest that fugitive emissions standards, 100 PPM, 500 PPM and 1000 PPM, are truly in the laminar flow region.

Hazardous Air Pollutants
*Relative Leakage Rates**

Table 2 – Liquids

HAP	Leakage Multiplier
Ammonia	9.80
Vinyl chloride	5.16
Formaldehyde	4.90
1, 3 Butadiene	4.26
Ethylene oxide	3.92
Hexatie	3.16
Chlorine	2.97
Phosgene	2.51
Methyl ethyl ketone	2.39
Toluene	1.78
Methanol	1.78
Trichloroethylene	1.63
Xylene	1.69
Benzene	1.63
Styrine	1.40
Cumene	1.32
Ethylene dichloride	1.13
Water*	1.00
Carbon tetrachloride	.98

Table 3 – Vapors/Gases

HAP	Leakage Multiplier
Cumene	2.86
Styrene	2.77
Xylene	2.77
Hexane	2.65
Toluene	2.59
Methyl ethyl ketone	2.46
1, 3 Butadiene	2.40
Benzene	2.34
Ethylene glycol	2.31
Ethylene dichloride	2.25
Ethylene oxide	1.91
Trichloroethylene	1.94
Carbon tetrachloride	1.86
Methanol	1.84
Formaldehyde	1.80
Ammonia	1.80
Vinyl chloride	1.68
Phosgene	1.53
Hydrogen sulfide	1.50
Chlorine	1.38
Air*	1.00

NOTE: The viscosity of gases/vapors increase with increasing temperature and are negligibly affected by pressure.

**Based on viscosities at 68°F or 78°F.*

Table 1A – Parts per Million Leakage (Volumetric) PPM(v)(2)

Drop or Bubble Diameter (in.)	Volume(1) Drop or Bubble (in^3)	Theoretical leak rate PPM(v)(3) bubbles per minute										
		4	5	6	8	10	16	20	25	32	50	64
1⁄32"	1.598×10^{-5}	9.5	0.6	0.8	1.0	1.3	2.1	2.6	3.3	4.2	6.5	8.4
1⁄16"	1.278×10^{-4}	4.2	5.2	6.3	8.4	10	17	21	26	34	52	67
3⁄32"	4.314×10^{-4}	14	18	21	28	35	57	71	88	113	177	226
1⁄8"	1.023×10^{-4}	34	42	50	67	84	134	168	210	268	419	536
5⁄32"	1.997×10^{-3}	65	82	98	131	164	262	327	409	524	818	1047
3⁄16"	3.451×10^{-3}	113	141	170	226	283	452	566	707	905	1414	1810

(1) Volume of drop or bubble = $\frac{\pi}{6}(\text{diameter})^3$

(2) Theoretical PPM(v) leak rate based on introducing the comparable bubble leak volume of a 100% methane gas into a pipe flowing pure air at 2 liters/minute.

(3) PPM = 491642 x leak rate (SCIS) @ 2 liters/minute flow rate. For flow rates larger than 2 liters/minute, the PPM would be proportionally smaller. For flow rates smaller than 2 liters/minute, the PPM would be proportionally larger.

Table 4a – Viscosities of Typical Test Fluids

Fluid	Viscosity Centipoise
Gas/Vapor	
Air	0.018 CP @ 60°F
Freon 114	0.015 CP @ 80°F
Helium	0.020 CP @ 70°F
Methane	0.011 CP @ 70°F
Nitrogen	0.018 CP @ 70°F
Propane	0.008 CP @ 32°F
Steam	0.013 CP @ 212°F
Liquid	
Kerosene	2.10 CP @ 60°F
Water	1.13 CP @ 60°F

Common Liquid Data

Viscosity Air @ 25°C = 180 MP
Viscosity Water Vapor @ 100°C = 130 MP
Viscosity Water @ 20°C =.98 CP or 9800 MP
Viscosity Propane Liquid @ 20°C = .12 CP
Viscosity Propane Vapor @ 20°C = 80 MP

Conversion Factors

0°C	32°F
20°C	68°F
25°C	77°F
50 Micropoise	0.005 Centipoise
90 Micropoise	0.009 Centipoise
100 Micropoise	0.010 Centipoise
200 Micropoise	0.020 Centipoise
1000 Micropoise	0.10 Centipoise
10000 Micropoise	1.00 Centipoise

Table 4 – Hazardous Air Pollutant Viscosities

Hazardous Air Pollutants[1]	Vapor Viscosity	Liquid Viscosity
	Micropoises	Centipoise
Acetaldehyde	85 MP @ 25°C	.22 CP @ 20°C
Acetonitrile	58 MP @ 25°C	.35 CP @ 25°C
Acrolein	80 MP @ 20°C	.36 CP @ 20°C
Acrylic acid	63 MP @ 25°C	.87 CP @ 25°C
Ammonia[2]	100 MP @ 20°C	.10 CP @ 25°C
Aniline	69 MP @ 25°C	2.4 CP @ 40°C
Benzene (including benzene from gasoline)	77 MP @ 25°C	.60 CP @ 20°C
Benzyl chloride	65 MP @ 25°C	1.27 CP @ 25°C
1,3-Butadiene	75 MP @ 20”C	.23 CP @ 20°C
Carbon disulfide	104 MP @ 25°C	.34 CP @ 25°C
Carbon tetrachloride	97 MP @ 20°C	.97 CP @ 20°C
Chlorine[2][3]	130 MP @ 20°C	.33 CP @ 20°C
Chlorobenzene	75 MP @ 25°C	.76 CP @ 25°C
Chloroform	100 MP @ 20°C	.58 CP @ 20°C
Cumone	63 MP @ 25°C	.74 CP @ 25”C
Dimetliyl formamide DMF	60 MP @ 25°C	.80 CP @ 25°C
Epichlorohydrin (1-Chloro-2,-3-Epoxybutane)	83 MP @ 20°C	1.25 CP @ 20°C
Ethyl acrylate	70 MP @ 25°C	.53 CP @ 25°C
Ethyl benzene	68 MP @ 25°C	.64 CP @ 25°C
Ethyl chloride (Cliloroethane)	95 MP @ 20°C	28 CP @ 20°C
Ethylene dibromide (Dibromoethane)	125 MP @ 50°C	1.7 CP @ 20°C
Ethylene dichloride (1,2-Dichlorethane)	80 MP @ 20°C	.87 CP @ 20°C
Ethylene glycol	78 MP @ 25°C	117.0 CP @ 25°C
Ethylene oxide	94 MP @ 25°C	.25 CP @ 25°C
Formaldehyde	100 MP @ 25°C	20 CP @ 0°C
Hexane	68 MP @ 25°C	.31 CP @ 25°C

Hazardous Air Pollutants[1]	Vapor Viscosity	Liquid Viscosity
	Micropoises	Centipoise
Hydazine	86 MP @ 25°C	.92 CP @ 25°C
Hydrogen sulfide[2]	120 MP @ 0°C	
Methanol	98 MP @ 25°C	.55 CP @ 25°C
Methyl bromide (Bromoethane)	124 MP @ 25°C	.32 CP @ 20°C
Methyl chloride (Chloromethane)	108 MP @ 20°C	.19 CP @ 20°C
Methyl chloroform (1,1,1-Trichloroethane)	93 MP @ 25°C	.80 CP @ 25°C
Methyl ethyl ketone (MEK) (2-Butanone)	73 MP @ 25°C	.41 CP @ 25°C
Methyi isobutyl ketone MIBK (Hexone)	67 MP @ 25°C	.57 CP @ 25°C
Methyl methacrylate	70 MP @ 25°C	.53 CP @ 25°C
Methyl chloride (Dichloromethane)	97 MP @ 20°C	.45 CP@ 20°C
Phosgene	118 MP @ 20°C	.39 CP @ 20°C
Propionaldehyde	78 MP @ 25°C	.36 CP @ 25°C
Propylene dichloride (1, 2-Dichloropropane)	74 MP @ 20°C	.86 CP @ 20°C
Propylene oxide	90 MP @ 25°C	.37 CP @ 25°C
Styrene	65 MP @ 25°C	.70 CP @ 25°C
Toluene	70 MP @ 25°C	.55 CP @ 25°C
Trichloroethylene	93 MP @ 20°C	.60 CP @ 20°C
Triethylamine TEA	73 MP @ 50°C	.39 CP @ 20°C
Vinyl acetate	80 MP @ 25°C	.43 CP @ 20°C
Vinyl chloride	107 MP @ 20°C	.19 CP @ 20°C
Vinylidene chloride (1,1-Dichloroethylene)	199 MP @ 20°C	.48 CP @ 2O°C
Xylenes (Isomers and mixers) (*M & P Xylene, **O-Xylene)	65 MP @ 25°C	.58 CP @ 25°C* .79 CP @ 25°C**

1) Viscosities are from Gallant Series, “Physical Properties of Hydrocarbons,” published in *Hydrocarbon Processing and Petroleum Refiners* (various issues) unless otherwise noted.

2) “A Treatise on Leakage,” Flowserve Vogt Valves technical paper.

3) “Chlorine Manual,” 1972 printing, Chlorine Institute.

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FCD VVABR1012-00 Printed in USA. (Replaces CB-12)

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