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# Correlations for Predicting Leakage Through Closed Valves

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U.S. DEPARTMENT OF COMMERCE
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# NBS TECHNICAL NOTE 355

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## CORRELATIONS FOR PREDICTING LEAKAGE THROUGH CLOSED VALVES

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Jesse Hord

## ABSTRACT

Safety, convenience, and economy often demand the inference of leakage of a given fluid from known leakage of another test fluid across valve seats, welded and threaded fittings, seals, etc. The temperatures of the fluids also may be different. An example is the prediction of gaseous hydrogen leakage at 20°K from test data obtained with nitrogen gas at 77°K. Various flow formulae (molecular, transition, and continuum) are examined, and two simple methods of correlating leakage for single-phase fluids are deduced. The correlations obtained (excluding transition flow through long channels) indicate the leakage is inversely proportional to the square root of the density, or inversely proportional to the absolute viscosity, of the fluid. Thus, for gases, the leakage is directly proportional to the sonic velocity of the gas. The proper relationship must be established by experiment for each valve, fitting, etc.

Key Words: Leakage through valves, leak rates, leak detection, predicting leak rates, valve seat leakage, leak flow rates, seal leakage.

## 1. Introduction

A large volume of literature has been devoted to detection and measurement of leakage flow and to the writing of leak test specifications. The problems involved in establishing meaningful specifications have been outlined by Hutchins[1] and Baumann[2]. Various flow theories have been utilized in some recent articles[2-10] to estimate leakage for specific problems; however, it appears there are no general guidelines for the inference of leakage of a given fluid from the known leakage of another test fluid. It is often desirable to leak test equipment with a non-hazardous fluid (at some convenient temperature) and then infer the leakage of a hazardous fluid (perhaps at a less convenient temperature). It is the purpose of this paper to provide these leakage correlations. There are many variables involved in a problem of this sort, and thus many assumptions are required to obtain useful engineering results. Although we are primarily concerned with valve seat leakage, the results are applicable to any leakage path (e. g. threaded and welded fittings, seals, etc. ). Thermal contraction and expansion of materials may alter the leak-path dimensions and make it quite difficult to correlate leakage results from one temperature to another. For valves, the seat seal resilience may change with temperature, and also the open-close cycle history affects the leakage as the seal wears in or wears out. Thus, it is obvious that correlating leakage from fluid-to-fluid and from one temperature to another is risky, and testing of the item in the actual use-environment is recommended; however, where correlation techniques must be used, the results of the following analysis are offered as guidelines. The flow formulae are given in volumetric form since leakage is normally quoted in volumetric units.

## 2. Correlation of Flow Formulae

In order to obtain useful engineering results, it is necessary to make several simplifying assumptions concerning the leakage flow:

a) The flow is isothermal for orifice flow in the molecular regime and for pipe flow in all regimes; this is normally a good assumption for relatively large-mass equipment with very little leakage.

b) Where continuum orifice flow applies, the leak-path cross section is considered small enough to neglect variations in velocity of approach, and the Reynolds number is large enough to assure a nearly constant discharge coefficient for all fluids at all inlet temperatures considered.

c) The pressure drop and absolute pressure levels across the leakage path are identical at all temperatures for all fluids. This assumption eliminates change in leak-path geometry with pressure.

d) The leak-path geometry does not change with temperature. For those cases where the geometry change may be computed with confidence, an area correction may be applied to the correlation.

e) The flow velocity does not exceed the velocity of sound in the fluid at specified conditions (i. e. adiabatic or isothermal flow, etc. ).

f) For all gases of concern, the ratio of specific heats and thus the critical (sonic flow) pressure ratio for orifices and nozzles do not differ appreciably. This is a good assumption for most gases over a wide range of temperatures at fairly low pressures. Variations in specific heat ratios cause relatively small changes[11] in the expansion factor, Y. The assumption of relatively small variations in specific heat ratios also permits isothermal and adiabatic acoustic velocity ratios to be interchanged. Isentropic conditions are assumed where critical flow occurs in orifices with contoured inlets.

g) For the case of viscous (Poiseuille) flow, the frictional resistance is assumed to vary from fluid to fluid; the friction factor is taken as constant in the turbulent flow formulae. Assumption of a constant friction requires either rough flow channels or relatively large Reynolds numbers, both of which appear tenable.

Additional assumptions which pertain to individual flow processes are noted in that which follows.

### 2.1 Free Molecule Flow Through Orifices and Short Channels or Through Long Channels ($Kn \geq 1$)

Knudsen flow applies when the gas mean free path is about equivalent to the smallest characteristic dimension of the flow duct (i.e. $Kn \approx 1$). The volumetric flow rate may be written in the form

$$Q = C_1 (\Delta P/P_1)(RT)^{1/2}, \tag{2.1a}$$

and the leakage $Q_A$ of fluid A at temperature A may be obtained from a known leakage $Q_B$ of fluid B at temperature B via

$$Q_A/Q_B = (R_A T_A/R_B T_B)^{1/2}. \tag{2.1b}$$

The constant in (2.1a) includes flow geometry parameters and consequently is different for long channels, short channels, and orifices, but the correlation result given by (2.1b) is the same (since the flow path geometry is assumed to remain unchanged with variations in temperature).

## 2.2 Continuum Flow Through Orifices ($Kn \leq 0.01$)

The volumetric flow rate for both compressible and incompressible fluids is given by

$$Q = C_2 Y(\Delta P/\rho_1)^{1/2}, \tag{2.2a}$$

and the correlating ratio is

$$Q_A/Q_B = (\rho_{1B}/\rho_{1A})^{1/2}. \tag{2.2b}$$

In (2.2a) $C_2$ involves the discharge coefficient and leak-path geometry, and Y is the expansion factor, all of which are invariant under the foregoing assumptions.

## 2.3 Viscous (Poiseuille) Flow Through Long Channels ($Kn \leq 0.01$)

The flow rate given here is subject to the restrictions of Poiseuille flow; i.e., incompressible, fully-developed laminar flow, through long, narrow channels. This formulation is valid for laminar, isothermal compressible flow where the Mach number is less than one-third [12].

$$Q = C_3 \Delta P/\mu, \tag{2.3a}$$

and the correlation factor is

$$Q_A/Q_B = \mu_B/\mu_A. \tag{2.3b}$$

Weiner [5] has presented some leakage flow nomographs based on Poiseuille flow relations and suggested basic criteria and definitions for fluid leakage. Some care must be taken in computing liquid leakage since surface tension can influence the results [5,8] when the leakage gap and flow rates are very small.

## 2.4 Turbulent, Incompressible Flow Through Long Channels ($Kn \leq 0.01$)

It is convenient to use constant frictional resistance to obtain

$$Q = C_4(\Delta P/f\bar{\rho})^{1/2}, \qquad (2.4a)$$

and

$$Q_A/Q_B = (\bar{\rho}_B/\bar{\rho}_A)^{1/2}. \qquad (2.4b)$$

The mean density is used to account for gas flow where it may be considered incompressible.

Steward [13] has suggested the friction factor be expressed as a function of Reynolds number and treated as a variable in (2.4a) to obtain a correlating ratio which accounts for viscosities in addition to densities. Using the relationship $f = \alpha/Re^{\beta}$ and performing the indicated algebra there results

$$Q_A/Q_B = \left(\frac{\bar{\rho}_B}{\bar{\rho}_A}\right)^{\frac{1-\beta}{2-\beta}} \left(\frac{\mu_B}{\mu_A}\right)^{\frac{\beta}{2-\beta}}. \qquad (2.4c)$$

Examination of (2.4c) indicates that the viscosity function is fairly weak for practical values of $\beta(\sim 0$ to $0.2)$, and the density function does not differ significantly from that of (2.4b). In consideration of the assumptions applied in the treatment of the various formulae in this paper, the refinement offered by (2.4c) is probably not warranted; however, it may have some limited application in liquid-to-gas or gas-to-liquid correlations where the test fluids are considered relatively incompressible and no phase change occurs across the leakage path. Equation (2.4c) is offered for reference only and is not applied to the general conclusions of this paper. Note that (2.4c) reduces to (2.3b) for laminar flow ($\beta = 1$) and is equivalent to (2.4b) for constant friction ($\beta = 0$). Use of (2.4c) requires experimental determination of $\beta$.

### 2.5 Transition Flow Through Orifices and Short Tubes ($0.01 < Kn < 1.0$)

Transition flow is intermediate to free molecule and continuum flow, and the theory for prediction of flow through orifices and short tubes in this region is not complete. Interpolation between free molecule and continuum formulae is common [14] for orifices; however, both the continuum and free molecule flow are inversely proportional to the square root of the density of the fluid, and thus produce identical correlating ratios (the equivalency of (2.1b) and (2.2b) is shown later). Some work on transition flow through orifices [15] and short tubes [16] was recently reported. Sreekanth [15] was able to correlate his experimental data for orifices with the theory for transition flow through long tubes by using a simple geometrical correction factor. Correlating ratios obtained from his formula would be identical to those for transition flow through long tubes.

### 2.6 Transition Flow Through Long Channels ($0.01 < Kn < 1.0$)

Transition flow through long channels is adequately represented by the summation of Knudsen and Poiseuille flow,

$$Q = [(C_1/\overline{P})(RT)^{1/2} + C_3/\mu]\,\Delta P. \qquad (2.6a)$$

Correlation of (2.6a) is slightly cumbersome and is obviously a combination of density and viscosity effects. This formula has been treated in the literature and will not be pursued further here. Guthrie and Wakerling [17] have capably handled the problem and tabulated data for several gases. Graham [10] has also expanded somewhat on this particular subject and provided detailed discussion on leak-rate specifications and testing. In addition, he discusses conversion of leakage rates to standard conditions. A bibliography and review of various leakage analyses has been prepared by Bauer, et al. [18]. Nomographs for incompressible and compressible viscous flow and transition flow through a circular interface are given [18].

## 2.7 Compressible Flow Through Long Channels ($Kn \leq 0.01$)

In addition to the foregoing formulae, we may write expressions for the flow of compressible fluids in long channels for i) isothermal flow, laminar or turbulent, with friction and ii) adiabatic flow with or without friction. In general, these equations are too complex for the cross-correlation desired here. As stated in the assumptions, the isothermal case is probably most prevalent. For the case of <u>isothermal compressible flow with constant friction</u>, the volume flow rate is

$$Q = C_5 \left( \frac{\Delta P/\bar{\rho}}{\ln (P_1/P_2) + F} \right)^{1/2}, \qquad (2.7a)$$

and the correlation is identical to (2.4b). Although the results would be rather cumbersome, the friction parameter in (2.7a) could be considered variable as in the development of (2.4c).

## 2.8 Critical Flow Through Orifices and Long Channels ($Kn \leq 0.01$)

When the downstream pressure is less than about 1/2 the upstream pressure, sonic flow may occur through nozzles or orifices with rounded inlets. It is usually very difficult to determine if critical flow exists in long channels, and the critical pressure ratio varies considerably. For flow at acoustic velocity, the volumetric flow rate in both orifices and pipes may be expressed by an equation of the form

$$Q = C_6 (RT)^{1/2}, \qquad (2.8a)$$

and is correlated by (2.1b). Vance [19] obtained an equivalent relationship in discussing the performance of throttling valves where sonic flow is attained; however, he states that "the volume flow ratio is proportional to the ratio of sonic velocities at inlet conditions and is independent of the gas or temperature." Obviously, this statement is erroneous.

### 2.9 Discussion of the Analytical Results

In considering assumption (c) we note that the mean density $\overline{\rho}$ and the upstream density $\rho_1$ are linearly related and consequently (2.2b) and (2.4b) produce identical results. Use of the ideal gas law shows (2.1b) is also identical to (2.2b) and (2.4b). Two very simple relationships are then deduced for use as leakage correlating factors from fluid-to-fluid (i.e., from one fluid at one temperature to another fluid at another temperature). The leakage rates are inversely proportional to the absolute viscosity or inversely proportional to the square root of the density of the respective fluids. For gases, the leakage rates are directly proportional to the sonic velocity in the gas. Perhaps the most useful way of presenting the results is

$$Q_A/Q_B = (\rho_{1B}/\rho_{1A})^{1/2}, \tag{2.9a}$$

or

$$Q_A/Q_B = \mu_B/\mu_A . \tag{2.9b}$$

It is recommended that experimental data be taken with two different fluids to establish the proper correlating procedure, i.e., (2.9a) or (2.9b) prior to inferring the leakage at the desired use-temperature. It is possible that in many cases the leakage may be bracketed by (2.9a) and

(2.9b), and the more pessimistic relation may be used. Equation (2.9a) is valid only for liquid-to-liquid or gas-to-gas correlations while (2.9b) may also be used for liquid-to-gas or gas-to-liquid correlations (within the framework of Poiseuille flow). Equation (2.9a) is limited to similar-phase correlations because the friction factor changes with fluid phase, and the compressible and incompressible formulae differ for both pipe and orifice flow. The correlating ratios developed are related to the volumetric flow of the individual fluids at their respective inlet temperatures. If it is desired to relate the leakage ratio to some reference temperature and pressure (e.g., STP), (2.9a) and (2.9b) must be multiplied by the appropriate density ratios. For gas-to-gas correlations at STP, (2.9a) and (2.9b) should be multiplied by $T_B/T_A$, and the results may be conveniently written

$$(Q_A/Q_B)_{STP} = [(T_B/T_A)(M_B/M_A)]^{1/2}, \qquad (2.9c)$$

or

$$(Q_A/Q_B)_{STP} = (\mu_B/\mu_A)(T_B/T_A). \qquad (2.9d)$$

## 3. Summary

Two very simple relations are deduced to aid in the inference of leakage through closed valves, etc. The leakage of fluid A at temperature A is obtained from the known leakage of fluid B at temperature B, and the results are summarized in table 3.1. The proper relationship must be established for each valve (or item) by testing with at least two different fluids, preferably at different temperatures. The two equations may be used to bracket the leakage and the more pessimistic formula used for inference of leakage at the use-temperature.

Equations (2.9a) and (2.9b) are recommended only when actual use-environment tests cannot be performed. Equation (2.4c) is applicable to liquid-to-gas or gas-to-liquid correlations for those particular cases where single-phase, incompressible flow can be assumed. Transition flow through long channels was not included in this summary since it has been capably treated in the literature[10, 17, 18]. None of the formulae presented here pertain to two-phase or mixed flow.

Table 3.1 Summary of Formulae

| Type of Flow | Applications & Restrictions | Correlating Ratio |
|---|---|---|
| Free Molecule Flow through orifices and short channels or through long channels | | |
| Subsonic continuum flow through orifices | Equation (2.9a) is limited to liquid-to-liquid or gas-to-gas computations | |
| Turbulent, incompressible flow through long channels with constant friction | | Eq. (2.9a) |
| *Transition flow through orifices | *Better results may be obtained by treating this case as transition flow through long tubes [15]. | |
| Isothermal compressible flow through long channels with constant friction | | |
| Critical flow through rounded-orifices, nozzles, and long channels | | |
| Viscous (Poiseuille) flow through long channels | Equation (2.9b) may be used for gas-to-gas, liquid-to-liquid, liquid-to-gas, or gas-to-liquid correlations as long as the requirements of Poiseuille flow are satisfied | Eq. (2.9b) |
| Transition flow through long channels | See References [10, 17, 18] Applies to gases only. | |

## 4. Nomenclature

$C$ = Constant in flow formulae

$F$ = Frictional resistance constant

$f$ = Friction factor ($\equiv \alpha/Re^{\beta}$)

$Kn$ = Knudsen number ($\equiv$ ratio of the mean-free path of the gas flowing through the duct to the smallest characteristic dimension of the duct), applied only to gas flow

$M$ = Molecular weight

$P_1$ = Upstream or inlet absolute pressure

$P_2$ = Downstream or exit absolute pressure

$\overline{P}$ = Arithmetic mean absolute pressure ($\equiv [P_1 + P_2]/2$)

$\Delta P$ = $P_1 - P_2$

$Q$ = Volumetric flow rate

$R$ = Gas constant, equals universal gas constant divided by the molecular weight

$Re$ = Reynolds number (based on flow area dimensions)

STP = Denotes standard temperature and pressure

$T$ = Absolute temperature of fluid at inlet conditions

$Y$ = Expansion factor in orifice formulae

### Greek

$\alpha$ = Constant in friction factor formula

$\beta$ = Constant in friction factor formula

$\rho_1$ = Upstream or inlet fluid density

$\rho_2$ = Downstream or exit fluid density

$\overline{\rho}$ = Arithmetic mean fluid density ($\equiv [\rho_1 + \rho_2]/2$)

$\mu$ = Absolute viscosity of the fluid at inlet conditions

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