Leak tightness and a proposed method for inhibiting water penetration of semi-tight containers

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Abstract

A practical way of characterising semi-tight containers in terms of a leak constant is suggested. In order to distinguish between vacuum-tight, semi-tight and open containers limits for the leak constant are established. A solution for infiltration of water into semi-tight containers is discussed and used for defining the maximum limit of the leak constant.

Nomenclature:

A	Area
b	Thickness
C_d	Discharge coefficient
d	Equivalent diameter
g	Gravitational constant
h	Height
K	Constant
K_o	Leak constant
ℓ	Length or width
M	Mole mass
m	Mass
$\triangle m$	Mass change
n	Specific mass or mass per unit area
Q	Volume flow
P	Pressure
R	Universal gas constant
r	Leak rate
T	Absolute temperature
V	Unoccupied or free volume in container
w	Mass flow rate
x	Dimension
y	Dimension
η	Efficiency
μ	Viscosity
ρ	Density
τ	Time
θ	Angle

Subscripts

b	Bag
c	Container
0	Atmospheric
1	Initial
2	Final
m	Max

Superscripts

*	Reference condition
–	Mean

1.0 Introduction

Containers, in general, can be classified as:
(i) vacuum-tight
(ii) semi-tight
(iii) open

Categories of leak tightness for vacuum-tight containers are well established in terms of pressure rating (Pa) and corresponding leak rate, defined as moles of gas per unit time leaking into a specified volume times the *numerical* value of the universal gas constant multiplied by the absolute temperature. Leak rate is therefore proportional to pressure times volume divided by time and unit volume and is usually measured in Pa.m³/s.m.³ or Pa.ℓ/s.ℓ. The categories of leak tightness arose from practical experience and this may be the reason why American and European standards differ as can be seen in table 1.

Table 1

Category of Vacuum	British and German Standards		American Standards
	Pressure Range (Pa)	Approximate corresponding leak rate (Pa.ℓ/s.ℓ)	Pressure range (Pa)
Extra Ultra High			$< 10^{-10}$
Ultra High	$< 10^{-6}$	10^{-7}	$10^{-10} - 10^{-7}$
Very High			$10^{-7} - 10^{-4}$
High	$10^{-6} - 10^{-1}$	$10^{-7} - 10^{-4}$	$10^{-4} - 10^{-1}$
Medium	$10^{-1} - 10^{2}$	$10^{-4} - 10^{-3}$	$10^{-1} - 3{,}3 \times 10^{3}$
Low or Rough	$10^{2} - 10^{5}$	$10^{-3} - 10^{-2}$	$3{,}3 \times 10^{3} - 10^{5}$

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There exists a need to characterise semi-tight containers in some similar fashion. Generally, semi-tight containers have internal pressures close to ambient pressure. However, since pressures and leak rates can change rapidly in semi-tight containers, it is more practical to define limits in terms of a so called leak constant. Pressure may change because of air lifting containers or because of temperature changes or barometric reasons.

One purpose of this paper is to suggest a way in which these leak constants can be obtained in order to distinguish a semi-tight container from an open or vacuum-tight one.

Examples of semi-tight containers are the following:

(i) storing containers of a particular kind
(ii) shipping containers of a special kind
(iii) diesel or other liquid fuel tanks
(iv) refrigerators and freezers
(v) gear boxes
(vi) certain sealed bearings

When normally closed containers are exposed to changing climatic conditions of temperature and humidity (including rain, snow, dew and frost) for a long period of time there exists the possibility of water penetration into the container. This could corrode either the contents or the container or both. Sometimes most expensive equipment can be totally destroyed if stored in these containers in the open under the above-mentioned climatic conditions.

Some proposed solutions to deal with the nett influx of water into semi-tight containers are the following:

(i) Use of water absorbing materials e.g. silicagel and activated alumina ($A\ell_2O_3$)
(ii) Use of corrosion or rust inhibitors
(iii) Water-tight bags in which equipment is placed before it is stored in the container
(iv) Improvement of seals on the containers
(v) Use of vacuum-containers or of a cover gas.

Sometimes solutions such as (iii) or (v) are not practical because certain equipment may intermittently be used and returned to a container.

The mechanism, according to which a nett influx of moisture into a semi-tight container may occur, can be explained as follows:

When a normally closed container is subject to climatic variations of temperature and humidity the pressure inside will decrease when temperature decreases. A pressure differential will develop across the lid of the container because the atmospheric pressure is substantially constant. Being semi-tight, air with a certain moisture content will be sucked into the container. If the temperature decrease is large, partial condensation of the water vapour in the air will occur. When the container heats up again during the normal increase of temperature during the day, the pressure inside increases and some of the air escapes again. The moisture content of this air may be lower than that of the air which entered because, depending on circumstances, the evaporation of the condensed water inside the container could be a relatively slow process. This cycle is repeated day by day and a slow build up of moisture inside the container may occur, provided the minimum temperature is below the condensation or desublimation points.

Water infiltration can happen also when a container is exposed to a rain storm where rapid cooling takes place. Some rain water may then be sucked in through the sealing surface.

Barometric changes and transporting containers across elevation gradients could also cause pressure differentials across container lids.

Another purpose of this paper is to suggest a solution for the infiltration of water into semi-tight containers and show how it may be used to define the maximum limit of leak rate for this type of container. The minimum value of leak rate is also determined.

2.0 Characterising a semi-tight container

It will be required to establish the outer limits of leak rates in order to characterise semi-tight containers. Air leakage into and out of containers, subjected to atmospheric conditions, may occur according to the following mechanisms:

(i) Turbulent flow
(ii) Laminar flow
(iii) Knudsen or molecular flow

Since atmospheric changes occur slowly and the dimensions of leakage channels through the seals of semi-tight containers are relatively small, the change for turbulent flow is very remote. Therefore only laminar and Knudsen flows are considered.

In general the mass flow rate through a leak can be expressed as:

$$\frac{dm}{d\tau} = -K(P - P_o) \qquad (1)$$

where the leak flow is into the container when $P < P_o$ and out of the container when $P > P_o$. P is the pressure inside the container and K = constant which depends on the type of flow.

Since m = mass of air in the free volume V of the container

$$m = \rho V = \frac{PMV}{RT} \approx \frac{PMV}{RT_o} \qquad (2)$$

because absolute air temperature inside a semi-tight container will normally be close to the atmospheric value.

Considering only small pressure changes and M, V, R and T_o as constant, equations 1 and 2 give

$$\frac{dP}{d\tau} = -K_o(P - P_o) \qquad (3)$$

where K_o = constant

$$K_o = \frac{A\rho_o d\, RT_o}{32V\mu\ell\, M} = \frac{AP_o d^2}{32V\mu\ell} \qquad (4)$$

for laminar

$$\text{and } K_o = \frac{4Ad}{3V\ell}\sqrt{\frac{RT_o}{2\pi M}} \qquad (5)$$

for Knudsen flow

Even if laminar and Knudsen flows occur simultaneously, as would happen in a practical case, the relationship given by equation 3 will still hold except that K_o will be a more complex function of
A, ρ_o, d, ℓ, π, M, R and T_o.

It will be difficult to calculate the value of K_o for a particular container. However, direct measurement, as shown in figure 1 and explained below, would be much easier.

From equation 3, after integration and substituting

$\triangle P^* = P^* - P_o$
= initial pressure difference across the container wall

at $\tau = 0$
and $\triangle P = P - P_o$
= pressure difference at any time τ

$$\text{it is found that } K_o = -\frac{1}{\tau}\ln\left(\frac{\triangle P}{\triangle P^*}\right) \qquad (6)$$

This is the defining equation for K_o, which may be called the leak constant of the container and which has the dimensions of the reciprocal of time (ie. s^{-1}).

Referring to figure 1, an ordinary water manometer or other differential pressure measuring device could be connected to the container as shown. An initial pressure difference can be obtained by either feeding a small amount of compressed air to the container or evacuating it slightly. After closing the valve the initial pressure difference, $\triangle P^*$, can be determined and the remaining difference, $\triangle P$, after a time τ has elapsed. K_o can then be calculated. To obtain a more accurate experimental value of K_o, several values of $\triangle P$ may be obtained at different time intervals. The slope of the regression curve fitted to these experimental points, on a semi-log scale will provide the value of K_o.

Table 2.0 gives practical values for K_o for a number of empty rubber sealed rectangular container boxes (internal volume approximately 0,3 m^3). The lids of these boxes were held down by a series of metal clips.

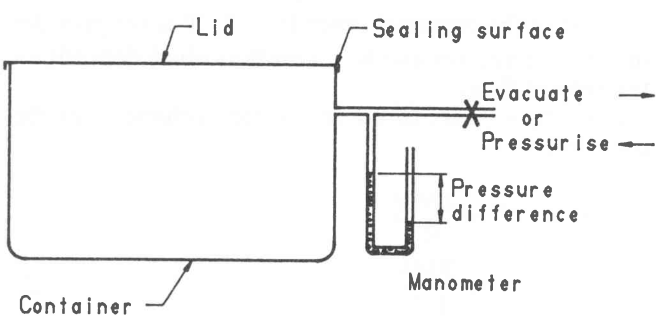

Figure 1

From table 2 it is clear that:

(i) That out-leakage constants are larger than in-leakage constants. This is to be expected because of the tendency of the higher internal pressure to force the lid open. In the case of in-leakage the lid is forced in the other direction.

(ii) Differences in K_o can be expected when the lid is removed and replaced or turned to a new position.

(iii) K_o for a particular type of container lies scattered within a rather broad band of values.

2.1 Definition of a semi-tight container

On account of practical considerations, which will be elaborated on, it is suggested that a semi-tight container is defined as a container for which the leak constant lies within the following range:

$$1 \times 10^{-1}s^{-1} \geq K_0 \geq 1 \times 10^{-7}s^{-1}$$

The upper limit of leak rate for vacuum-tight containers is approximately $10^{-2}\ \frac{Pa.\ell}{s.\ell}$ or $\frac{Pa.m^3.}{s.m.^3}$. In Order to have a smooth transition between "vacuum-tight" and "semi-tight" containers the lower limit of semi-tight containers should correspond with the upper limit of vacuum-tight containers.

The mass flow rate of air which corresponds with 10^{-2} $Pa.m^3/s.m^3$

$$w = \frac{PQM}{RT} = \frac{10^{-2} \times 29}{8316{,}6 \times 293}$$
$$= 1{,}19 \times 10^{-7} \text{ kg/s at a temperature of 20 C.}$$

Table 2

Container number	K_o in leakage (s^{-1})	K_o out-leakage s^{-1}	K_o in-leakage (lid removed and replaced) (s^{-1})	in-leakage (with lid turned through 180°) (s^{-1})
1	0,024	0,038	0,025	0,028
2	0,034	0,048	0,036	0,031
3	0,090	0,120	0,088	0,060
4	0,080	0,094	0,085	0,083
5	0,051	0,064	0,0420	0,059
6	0,037	0,050	0,033	0,034

Semi-tight containers are subjected to atmospheric temperature changes which has a period of 24 hours. Normally temperature, and therefore pressure inside a container, will drop during one half (12 h) of this period and rise during the other half. It is clear that an average period of 12 hours should be chosen e.g. for inleakage of air. If it is assumed that a container of one m^3 was initially fully evacuated, then the total mass which would leak into the container during a 12 hour period would be

$$\begin{aligned}\triangle m &= w \times 12 \times 3\,600 \\ &= 5{,}141 \times 10^{-3} \text{ kg of air}\end{aligned}$$

The mass of air in one m^3 at an atmospheric pressure of 100kPa and a temperature of 20 C will be

$$\begin{aligned}m &= \rho = \frac{PM}{RT} \\ &= \frac{10^5 \times 29}{8316{,}6 \times 293} \\ &= 1{,}19 \text{ kg/m}^3\end{aligned}$$

If the container is cooled down and a mass of $\triangle m = 5{,}141 \times 10^{-3}$ kg allowed to leak in a over a 12 hour period than, after suddenly returning to 20° C the corresponding pressure change due to the mass change would be

$$= \frac{1{,}19 + 0{,}05741}{1{,}19} = 1{,}00432$$

or about 0,432%

In terms of equation 6 it is clear that when

$$\frac{\triangle P}{\triangle P^*} = (1\text{-}0{,}00432) \text{ after 12 h}$$

$$\begin{aligned}K_0 &= -\frac{-1}{12 \times 3600} \ln 0{,}99568 \quad s^{-1} \\ &= 1{,}002 \times 10^{-7} \quad s^{-1} \\ &\approx 1 \times 10^{-7} \quad s^{-1}, \quad \text{the proposed lower limit}\end{aligned}$$

It can be shown from equations 1, 2 and 3 that, by assuming $P = O$, the relationship between the leak rate r and the leak constant K_0 is given by

$$r = P_0 K_0 \tag{7}$$

The SI unit of r is either Pa/s or $\frac{\text{Pa m}^3}{\text{s.m}^3}$

The upper limit of K_0 is tied to a proposed solution for preventing atmospheric air entering a container. This will be discussed in the next paragraph.

3.0 PROPOSED METHOD FOR INHIBITING ATMOSPHERIC AIR OR WATER PENETRATION OF SEMI-TIGHT CONTAINERS AND ITS EFFICIENCY

In accordance with a proposed method inhibiting water penetration of semi-tight containers, a normally rigid container is provided with a movable wall portion or flexible water-tight breathing bag to vary the internal container volume and causing any pressure difference, between the container inside and outside, to be approximately cancelled by wall or bag movement under influence of the pressure difference. When a "breathing" bag is used, the bag mouth is sealed and secured to an opening in the container wall with the bag interior in communication with the exterior of the container as schematically illustrated in a cross-sectional view of the container in figure 2.

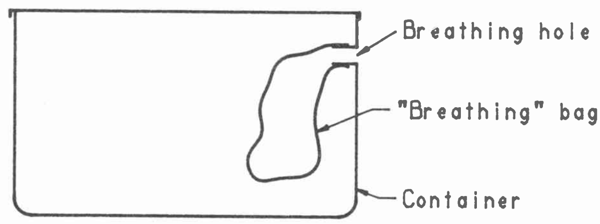

Fig 2

The method would have been ideal if a weightless and totally flexible bag was available. However the specific mass of the material, expressed as mass per unit area of the bag material, and its flexibility must be considered since it will influence the driving pressure difference which operates the bag.

If one considers e.g. 1 m area of the upper side of a half filled bag lying on the floor of a container as shown in fig 3.,

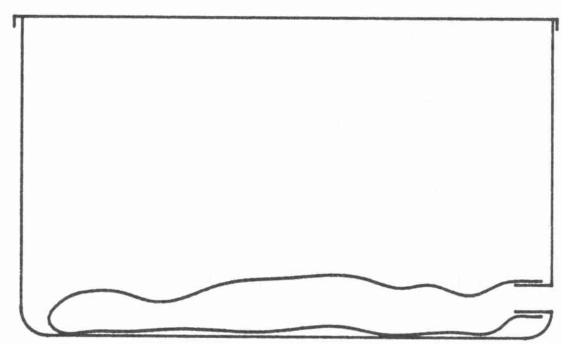
Fig 3

it is clear that the gravitational force due to the weight of the bag material will create a "back"-pressure difference if the container is in a cooling phase.

This "back"-pressure difference can easily be calculated from

$$\triangle P_b = \frac{n_b a_b g}{A_b} \tag{8}$$

$$= n_b . g$$

$$\approx 10\, n_b \text{ Pa} \tag{9}$$

if it is assumed that $g \approx 10$ m/s and n_b is given in kg/m.

$\triangle P_b$ represents a constant resistance which must be overcome before the bag can be useful, for example during a cooling period. This pressure difference can also be regarded as a constant difference which will cause in-leakage because of the tendency of the top side of the bag to act like a piston under its own weight increasing the free volume inside the container.

If the bag posesses stiffness its effect must be included in $\triangle P_b$. Normally the total $\triangle P_b$ would have to be determined experimentally for practical cases.

It is now assumed that $\triangle P_b$ is small and constant during a normal 12 hour cooling period of a daily cycle.

Using equation 3 with

$$(P - P_0) = \triangle P_b = \text{constant} \qquad (10)$$

and equation 2, it follows that

$$\frac{dm}{d\tau} = -K_0 \triangle P_b \frac{MV}{RT_0} \qquad (11)$$

Integrating this equation over a period of 12 hours, and using equation 9, the mass of air which will leak in can be shown to be

$$\triangle m_b = 4{,}32 \times 10^5 K_0 n_b \frac{MV}{RT_0} \text{ kg} \qquad (12)$$

If SI units are used.

Using the ideal gas law, it can be shown that the mass of air passing into or out of a container during a temperature change will be given by

$$\begin{aligned}\triangle m_c &= \frac{P_1 MV}{RT_1}\left(1 - \frac{P_2 T_1}{P_1 T_2}\right) \\ &= \triangle m_c \left(1 - \frac{P_2 T_1}{P_1 T_2}\right) \qquad (13)\end{aligned}$$

Where m_c = mass of air in the free space inside the container. Since there is not much of a pressure change in a container at a fixed geographical location (larger changes occur when a container is air-lifted)

$$\begin{aligned}P_2 &\approx P_1 \\ \frac{\triangle m_c}{m_c} &\approx \left(1 - \frac{T_1}{T_2}\right) \\ &\approx \frac{V_b}{V} \qquad (14)\end{aligned}$$

where V_b is the minimum bag volume required for a temperature change between T_1 and T_2. Typical extreme values on the same day for a container in the open would be

$T_1 = 273 + 0 = 273$ K
$T_2 = 273 + 50 = 323$ K

since air inside a container could get quite hot, even on a winter's day.
Therefore $V_b = 0{,}18$ V, which means that the minimum bag volume should be approximately 18% of the free volume in the container.

3.1 Bag efficiency

To determine bag efficiency the average mass of air which would leak into a container during a specified number of 12 hour periods must be calculated. If it is assumed that $\left(\frac{T_{min}}{T_{max}}\right)_{ave}$ is the average temperature ratio of minimum and maximum temperatures, which the container may be subjected to, then, using equation 13, the average mass of air which would leak in during a day without a bag present will be

$$\triangle m_c = \frac{P_o MV}{RT_{min}}\left\{1 - \left(\frac{T_{min}}{T_{max}}\right)_{ave}\right\} \qquad (15)$$

Assume $T_{min} \approx T_o$ and using 12 the ratio

$$\frac{\triangle m_b}{\triangle m_c} = \frac{4{,}32 \times 10^{-5} K_o n_b}{P_o\left\{1 - \left(\frac{T_{min}}{T_{max}}\right)_{ave}\right\}} = y$$

y is the ratio of the fraction of air which would flow into a container with a bag present to the fraction which would flow in without a bag. It is now possible to define an efficiency for an ideal bag namely

$$\begin{aligned}\eta_b &\equiv (1 - y) \times 100\% \\ &= \left[-\frac{4{,}32 \times 10^{-5} K_o n_b}{P_o\left\{1 - \left(\frac{T_{min}}{T_{max}}\right)_{ave}\right\}}\right] \times 100\% \qquad (16)\end{aligned}$$

with P_0 in Pa, K_0 in s^{-1} and n_b in kg/m

From the equation it is clear that the bag efficiency will improve for smaller n_b, smaller $T(_{min}/T_{max})_{ave}$, smaller K_0 and larger P_0. Substituting the following extreme, but practical values for n_b, $(T_{min}/T_{max})_{ave}$ and P_0 into the above equation namely

$n_b = 0{,}02$ kg/m (an extremely light flimsy bag)
$(T_{min}/T_{max})_{ave} = 0{,}9$
$P_0 = 90\,000$Pa
and $K_0 = 0{,}1$
it is found that
$\eta_b \approx 90\%$

3.2 Improving bag efficiency:—

The bag efficiency can be improved by suspending the bag vertically, thus effectively reducing the gravitational force. It is assumed that the shape of a suspended bag can be approximated as shown in fig 4.

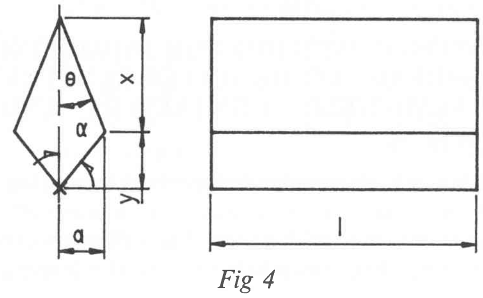

Fig 4

Taking a force balance on the suspended bag the effective pressure difference is given by

$$\triangle P_b = \frac{g\ell n_b\left\{\frac{x}{\cos\theta}.\sin\theta - \frac{y}{\sin\alpha}\sin\alpha\right\}}{h\ell}$$

$$= \frac{gn_b}{h}\{x\tan\theta - y\tan\alpha\}$$

where h = height of the bag when empty

But $a = x\tan\theta = y\tan\alpha$

$$\triangle P_b = 0 \qquad (17)$$

Substituting this result into equations 11 and 16 means that $\eta_b = 100\%$ for a vertically suspended ideally flexible bag hanging in the shape as assumed.

In practice one would prefer a bag with an efficiency of 90% or more. Considering all the limits on η_b, P_0, flexibility, possible vertical suspension etc., it seems that the upper defining limit for K_0 will be of the order of 10^{-1} for a practical semi-tight container.

3.3 Minimum size of the breathing hole

To ensure that the breathing hole, which forms the connection between the inside of the breathing bag and the atmosphere, would not restrict flow, its diameter should be large enough.

The mean mass flow during a 12 hour period when flow is passing into a bag is given by

$$\bar{w} = \frac{m}{\tau} = m\left(1 - \frac{T_{min}}{T_{max}}\right)\frac{1}{12 \times 3\,600} \qquad (18)$$

Climatic temperature changes can be approximated by a sine wave and the maximum mass flow rate will then be

$$w_m = \frac{\pi}{2}\bar{w} = 3{,}636 \times 10^{-5}\frac{P_oMV}{RT_{min}}\left(1 - \frac{T_{min}}{T_{max}}\right) \qquad (19)$$

It is assumed that laminar flow occurs. Applying equations 1, 4 and 19 the maximum pressure difference across the breathing hole will be

$$\triangle P_{b_m} = \frac{w_mRT_o}{K_oV\,M} \qquad (20)$$

Requiring (arbitrarily) that

$$\triangle P_{b_m} \leq \frac{1}{100} \times \triangle P_b$$

$$\leq \frac{n_b}{10} \qquad (21)$$

e.i. $\triangle P_{b_m}$ must never exceed 1% of the pressure difference caused by the bag.

For a round hole $A = \frac{\pi}{2}d$

the minimum diameter of the breathing hole will then be

$$d_{min} \geq \left[\frac{\mu\ell V}{135\,n_b}\left(\frac{T_{max}}{T_{min}} - \frac{T_{min}}{T_{max}}\right)\right]^{0,25} \qquad (22)$$

where ℓ = effective length of the hole and T_0 is assumed $= \frac{T_{min} + T_{max}}{2}$. subsituting the following typical values for the different parameters namely

$T_{min}/T_{max} = 0{,}85$
$\mu = 1{,}85 \times 10^{-5}$ kg/m.s
$\ell = 0{,}02$ m
$V = 1{,}0$ m³
$n_b = 0{,}1$ kg/m
it is found that
$d_{min} \geq 9{,}7$ mm

3.4 General requirements for a breathing bag

For practical application of a breathing bag the following general requirements hold:

i) Minimum volume
ii) Water-tight or leak-tight in general
iii) Light as possible
iv) Flexible as possible
v) Tough and abrasion resistant especially when equipmnt is removed or installed
vi) Non corrodable
vii) Should not oxidise
viii) Should be easily installed
ix) The breathing hole should be of minimum size, not inhibiting breathing, and placed in such a position that rain water is prevented from entering the bag and water is drained out of the bag.
x) The breathing hole should not easily be clogged.

Depending on a particular application, a breathing bag can be protected by installing it in a separate compartment or secondary container within the main containing device. The only requirement would be that adequate flow exchange area must exist at the boundaries between the compartment or secondary container and the main container.

4.0 References

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