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PERMEABILITY COEFFICIENTS OF SUSTAINABLE GASES THROUGH PLASTIC PIPES

Suzanne van Greuningen
Kiwa Technology
the Netherlands

Ernst van der Stok
Kiwa Technology
the Netherlands

SHORT SUMMARY

This paper gives a comprehensive overview of the permeability coefficients of PE, PA, and PVC materials for a variety of gases (hydrogen, methane and carbon dioxide) and the means to assess the impact of permeation in a gas transport or distribution system.

KEYWORDS

Permeation, polyethylene, polyamide, polyvinyl chloride, hydrogen, carbon dioxide, methane, GWP

ABSTRACT

Methane is a powerful greenhouse gas. Limiting methane emissions, substituting carbon-based fossil fuels with green alternatives such as hydrogen and deploying carbon capture and storage (CCS) are vital to limit global warming.

Leakages in the gas network are the largest source of gas emissions in the gas transport and distribution sector. Nevertheless, the contribution of permeation to gas emissions cannot be neglected, and not only from an environmental point of view. Estimating these values also sheds light on the economic effects arising from loss of the transported gas and possible safety risks due to accumulation of the permeated gas.

Gas losses due to the naturally occurring, unavoidable process of permeation are quantified as the ‘permeation rate’ (gas volume per period of time). Estimating permeation losses requires details of the gas network, including its dimensions, the partial pressure difference and the permeability coefficient. The permeability coefficient is a material characteristic that is strongly dependent on the type of gas and temperature. A suitable permeability coefficient is required to accurately estimate the permeation rate of methane, hydrogen or carbon dioxide through a gas distribution network.

The permeability coefficients of gases for different types and grades of PVC, PE and PA pipes under different temperature and pressure conditions have been, and continue, to be determined experimentally by many different laboratories. The volume of data available from literature is therefore extensive and constantly growing. However, the experiments described in literature were carried out under a variety of different circumstances (e.g. sample shape, temperature and pressure) and the results are reported in a wide range of units. Selecting a suitable permeability coefficient from these data can therefore be a complex and extensive task. Moreover, an unsuitable permeability coefficient can lead to an overestimation or underestimation of the permeation rate of a network.

To facilitate the selection process, this paper gives the permeability coefficients from over twenty different literature sources and presents a comprehensive overview of the experimental conditions. The coefficients have been recalculated to equalise the units and operating conditions. The paper also explains how these permeability coefficients can be used to calculate the permeation rate of a given gas network for any dimensions and operating pressure. This establishes an accessible method for estimating the permeation rate of methane, hydrogen and carbon dioxide for PVC, PE and PA piping systems.

INTRODUCTION

All plastic materials exhibit some degree of gas permeation. Permeation is a naturally occurring process in which the permeate (a gas) passes through a solid barrier material (e.g. a polymer). Note that permeation is different from a leak, in which no physical barrier exists. The leakage rate will thus be much higher than the permeation rate of a gas. Furthermore, the permeated gas is distributed over the entire surface area of the pipe system, while a leak is concentrated at a single location.

Unfortunately, the permeability coefficient, which represents the permeation rate under specific conditions, varies significantly between different polymers. The current climate means it is essential to be able to estimate greenhouse gas losses and their impact on climate change.

To accurately estimate these volumes, this paper gives the method for calculation of the permeation rate of a gas distribution network and a list of suitable permeability coefficients of methane, hydrogen or carbon dioxide under different conditions. The paper also demonstrates how the permeability coefficients as can be found in literature can be conveniently converted into a variety of preferred units by using conversion factors. Finally, the global warming potential (GWP) of different gases is given to allow the quantity of energy that the emission of 1 tonne of a gas will absorb over a given period of time to be calculated, relative to the emission of 1 tonne of carbon dioxide (CO_2).

METHODS AND CONDITIONS FOR PERMEABILITY TESTING

There are various test methods for determining the gas permeation rate, which can be used to deduce the permeability coefficient of a material. The film and sheeting method and pipe in jacket pipe permeation test method are the methods most commonly encountered in literature. Both methods are based on a pressure differential applied across a barrier layer. The film and sheeting method is very suitable for small specimens and for comparing the performance of different materials in a single test run. Testing a pipe specimen is a method that closely resembles the situation in practice, which makes it easier to understand for clients and other interested parties if a proof of concept is the purpose of the research. Brief explanations of the test methods are given below.

Film and sheeting method

The film and sheeting method is based on the method described in ISO 15105-2. The test setup consists of ‘containers’. A specimen is placed in each of these (Figure 1, the right photo shows three containers). Each specimen is placed between the two stainless steel discs (Figure 2, top) of a container, which are then tightly fastened with bolts. To prevent bending of the specimen due to high primary pressure, the specimen on the secondary disc is supported by a labyrinth (Figure 2, top left disc). Rubber O-rings between each disc and specimen seal the container against leaks.

The test setup can be placed inside an oven or climate chamber to ensure constant temperature during testing. The temperature can be continuously monitored using thermocouples. After conditioning, the specimen is gradually pressurised up to the desired test pressure on the primary side and left at a small overpressure compared to the test pressure. The pressure on the primary side is monitored continuously and the system is repressurised when needed to ensure that the primary pressure remains within tolerance. The secondary side is filled with another (often inert) gas at atmospheric pressure. Due to the partial pressure difference, the test gas will permeate from the primary side through the specimen to the secondary side. There are several methods available for measuring the amount of gas that permeates through a specimen, including using a coulometric sensor, a gas chromatographic sensor or a pressure sensor. In the setup described here, the increase in the volume of the test gas on the secondary side is measured using a pressure measurement system. The pressure increase due to permeation of the test gas can be used to calculate the volume increase. This is done by correlating the pressure increase of the test gas with the pressure increase of a known volume, which is established prior to testing. The following equation describes the relationship:

$$V_{accumulated\ gas} = \frac{P_{known} \cdot V_{known}}{P_{accumulated\ gas}} \qquad (1)$$

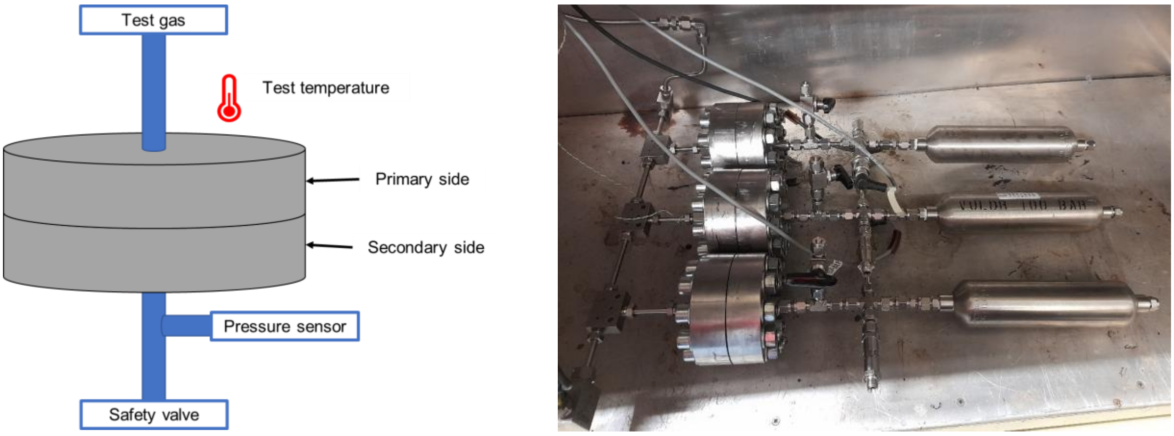

Figure 1: Test setup for film and sheeting permeation measurements. A schematic representation of the disc setup with inlet, outlet, pressure sensor and safety valve is shown on the left. The actual setup with three discs connected to the test gas inlet and small tanks on the secondary side to collect the permeate is shown on the right.

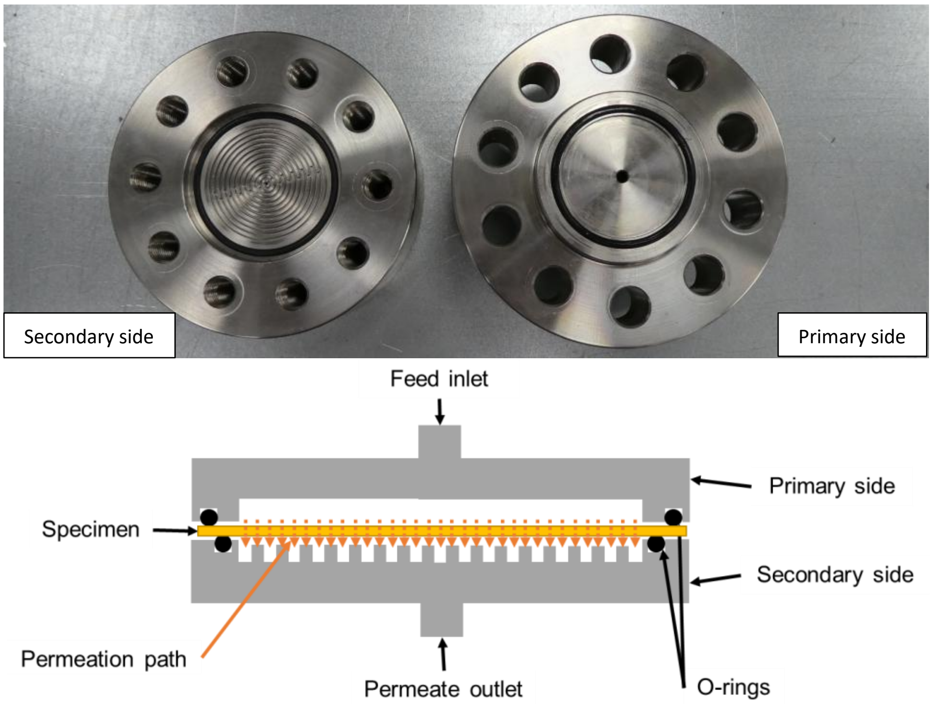

Figure 2: The specimen holder for the film and sheeting permeation test. The primary side disc (right) and the secondary side disc with supporting labyrinth (left) are shown at the top. A schematic representation of the sample holder showing the sealing O-rings and the permeation path through the specimen is shown at the bottom.

Pipe in jacket pipe method

With the pipe in jacket pipe method, a steel jacket pipe is placed around a pipe sample. Mechanical or welded end caps are used to close off the pipe ends on both sides. A schematic representation of the test setup is shown in Figure 3. The jacket pipe is flushed and subsequently filled with an inert gas and left at a small overpressure. The pipe is then flushed with pure test gas and pressurised to the desired testing pressure.

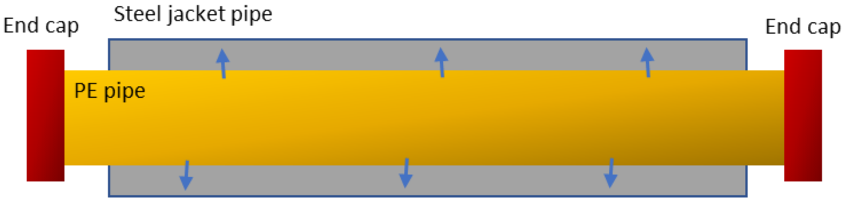

Figure 3: Schematic representation of the test setup for the jacket pipe method.

The test setup can be placed in a climate chamber to ensure a stable environment and limit the effect of temperature fluctuations. The pressure inside the pipe sample is monitored closely and kept as stable as possible. The pipe is repressurised when necessary.

Due to the pressure difference, the test gas will permeate through the pipe sample and accumulate in the steel jacket pipe. The concentration of hydrogen in the jacket pipes is measured at specific times using a gas chromatograph. Before each measurement, the system is calibrated using calibration gases with a known concentration of the test gas. The calibration gas is selected to match the concentration of the test gas in the steel jacket pipe as closely as possible.

Calculating the permeability coefficient

Whichever method is used, the film and sheeting method or pipe in jacket pipe method, it will take some time before the test gas reaches the secondary volume or jacket pipe. After some time, a steady flow of test gas permeates through the polymeric barrier. This will continue until the driving force decreases, i.e. the partial pressure difference falls due to a possible concentration increase in the secondary volume or jacket pipe.

A typical permeation curve is shown in Figure 4 [1]. The accumulated permeate can be determined from the concentration as measured with a gas chromatograph or the partial pressure increase. The stable increase in accumulation of the gas (last six datapoints of the curve) can be used to calculate the permeability coefficient, depending on the slope of the curve (the flow *Q*), the difference in partial pressure (Δ*p*), the surface area of the barrier[1] (*A*) and the thickness of the barrier (*e*) using the equation:

$$P_C = \frac{Q \cdot e}{A \cdot \Delta p} \qquad (2)$$

By extrapolating the steady state part of the curve back to the x-axis, this breakthrough time (*BT*) can be used to calculate the diffusion coefficient (*D*) [2, 3]:

$$D = \frac{e^2}{(6 \cdot BT)} \qquad (3)$$

The solubility (*S*) can then be calculated following [2, 4]:

$$S = \frac{P_C}{D} \qquad (4)$$

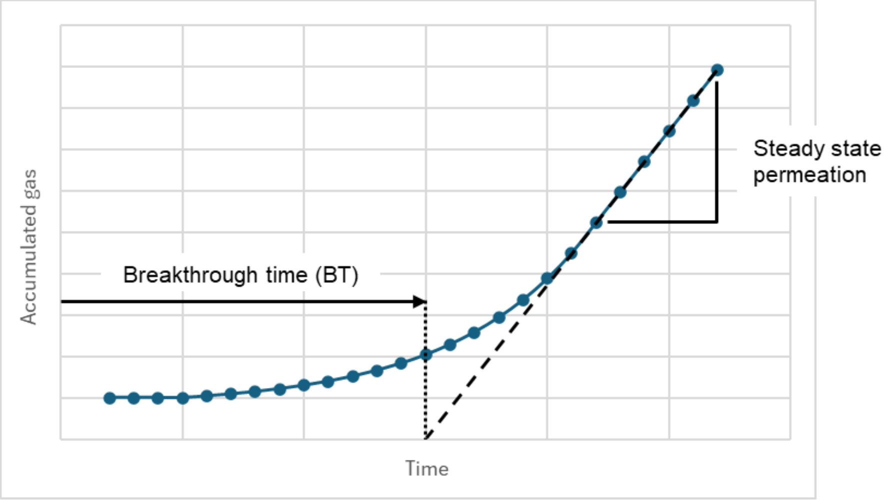

Figure 4: Schematic representation of the increase in permeate over time in the secondary volume or jacket pipe.

Condition temperature and pressure are important constraints

An empirical relationship between temperature and permeability coefficient

The permeation rate of the various components through the piping material is highly dependent on the mobility of the molecules. This includes both the movement of the polymer chains and the movement of the permeate. The movement of molecules is strongly influenced by temperature. A high temperature means more energy and therefore greater molecular mobility. The permeation rate is thus also higher at higher

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[1] For pipes, this can be approximated using the median diameter [14].

temperatures. [5] describes how the relationship between temperature and the permeability coefficient follows Arrhenius' law as expressed by the following equation:

$$P_c = P_{C0} \cdot e^{\left(\frac{-E_{Pc}}{R \cdot T}\right)} \qquad (5)$$

Where ‘P_C’ is the permeability coefficient in [(ml·mm)/(m^2·bar·day)], ‘P_{C0}’ is the pre-exponential factor of the permeability coefficient [(ml·mm)/(m^2·bar·day)] -a constant-, ‘E_{Pc}’ is the activation energy in [J/mol], R is the molar gas constant, 8.314 [J/(K·mol)], and T is the temperature in [K].

Pressure dependence of permeability

Small variations in gas pressure do not fundamentally affect the permeation mechanism. It can therefore easily be corrected for in the permeability coefficient. However, significant pressure differences can lead to variations in permeation behaviour. The effect of pressure on permeability depends on the gas in question. This is described in [6], in which the permeability of LDPE and PP at 25 °C was determined for pressures ranging from 0 to 130 atm (1 atm equals ~1 bar) (Figure 5). The permeability coefficient of LDPE for hydrogen gas remains nearly constant despite pressure variations. However, the permeability coefficient for carbon dioxide rises quite steeply. The same is true for methane to a slightly lesser extent. Measurements are necessary to correctly assess whether the change in pressure causes the permeability coefficient to remain equal, decrease or increase. As the operating pressure of the Dutch gas distribution grid lies between the 30 mbar and 8 bar[2], the effect of pressure on the permeability coefficients is limited. However, for reinforced thermoplastic pipes, the pressure may be much higher (e.g. 42 bar(g) [7]). Although the effect of pressure may be small, performing the experiment using gas pressures corresponding to operating conditions when testing is recommended.

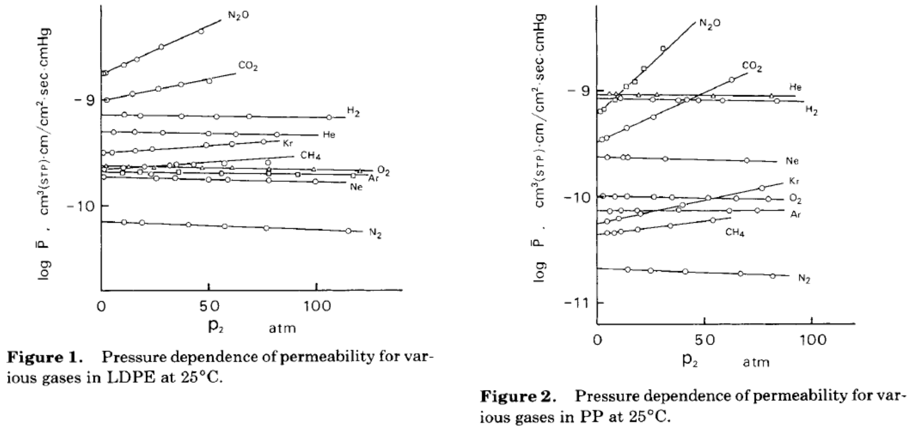

Figure 1. Pressure dependence of permeability for various gases in LDPE at 25°C.

Figure 2. Pressure dependence of permeability for various gases in PP at 25°C.

Figure 5: The influence of gas pressure on the permeability of LDPE and PP for various gases. Source [6].

Conversion factors to recalculate values into different units

Various units are used to express the permeability coefficient in different countries across the globe. The International System of Units, or SI system, is the metric system of uniform international standard units for measuring quantities. Using the units (ml·mm)/(m^2·bar·day) is therefore recommended, as this results in an easy-to-read value without exponentials. Preferences may however vary, which necessitates conversion into alternative units. A list of frequently used units and conversion factors has been compiled to facilitate this process.

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[2] The maximum operating pressure in the Dutch gas grid is 200 mbar(g) for PVC and 8 bar(g) for PE.

Table 1: Conversion factors used to convert permeability coefficients in (ml·mm)/(m^2·bar·day) into several different units.

Preferred units	Conversion factor
(cm^3 i.N · mm) / (m^2 · bar · day)	/ (1 · 1) · (1 · 1 · 1)
(ft^3 · mil) / (ft^2 · day · psig)	/ (28317 · 0.0254) · (0.0929 · 1 · 0.06895)
(µm · mm) / (m^2 · atm · day)	/ (1 · 0.001) · (1 · 1 · 1.013)
(cm^2 · cm^3 (STP)) / (cm^3 · Pa · s)	/ (1 · 10) · (0.0001· 0.00001 · $1.15641 \cdot 10^{-5}$
(cm^3 (STP) · mm) / (cm^2 · cmHg · s)	/ (1 · 1) · (0.0001 · 0.01333· $1.15741 \cdot 10^{-5}$
(mol · m^2) / (m^3 · MPa · s)	/ (24500 · 1000) · (1 · 10 · $1.15741 \cdot 10^{-5}$)

RANGE OF PERMEABILITY COEFFICIENTS OF DIFFERENT MATERIALS AND GASES

The permeability coefficient (P_c) is a material characteristic and a measure of the resistance of a material to permeation. The permeability coefficient is a part of the equation used to calculate the permeated volume flow (Q) (Equation 2). Other factors required for this equation are the surface area of the barrier (A), which is calculated from the length and median diameter of the pipe, the thickness of the barrier, which is represented by the wall thickness (e), and the difference in partial pressure (Δp), which is the difference between the pressure of the transported gas on either side of the pipe wall. The surface area, wall thickness and partial pressure are characteristic of the network system or pipe under consideration and are known factors. However, the permeability coefficient varies significantly for different gases and between different polymers. As mentioned above, it is highly temperature dependent and to a lesser extent in the case of some gases also pressure dependent. Selecting a suitable permeability coefficient can therefore be difficult. A comprehensive overview of permeability coefficients obtained from experiments under 16 bar(g) conditions has therefore been compiled. A few values were extrapolated using Arrhenius' law.

Permeability coefficients for PE

Table 2: Typical range of permeability coefficients of PE 80, PE 100 and PE 100-RC for hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) in (ml·mm)/(m^2·bar·day). Literature sources: [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18].

	8 °C	20-25 °C	40 °C
H_2	55 - 89	108 - 193	299 - 523
CH_4	6 - 9	10 - 37	98 - 165
CO_2	Unknown	136 - 279	Unknown

Permeability coefficients for PVC

Table 3: Typical range of permeability coefficients of high impact PVC (PVC-HI), unplasticized PVC (PVC-U), biaxially orientated PVC (PVC-O) for hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) in (ml·mm)/(m^2·bar·day). Literature sources: [11], [17], [19], [20], [21], [22], [23].

	8 °C	20-25 °C	40 °C
H_2	47.6	79.7 - 181.3	Unknown
CH_4	0.3	0.5 - 3.7	6.4
CO_2	2.6	7 - 10.4	30.2

Permeability coefficients for PA

Table 4: Typical range of permeability coefficients of PA11, PA12 for hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) in (ml·mm)/(m^2·bar·day). Literature sources: [17], [21], [24], [25], [26], [27], [28].

	8 °C	20-25 °C	40 °C
H_2	32.7 - 47.4	51.3 - 95.8	160.1 - 249.5
CH_4	2.3	0.38 - 5.8	17.2
CO_2	15.3	27.1 - 58.3	65.1

CALCULATING THE PERMEATION RATE OF A NETWORK

The permeated volume flow of a gas (Q_V) through a pipe or network depends on the permeability coefficient (P_C) of the material, the partial pressure difference of the permeate (ΔP) and the dimensions of the pipe; the length (L) and median diameter (D_m) are used to calculate the surface area (A) and wall thickness (e). The permeation rate for a pipe at a specific temperature can be approximated [24] by:

$$Q_\mathrm{V} = \frac{P_\mathrm{c} \cdot (d_\mathrm{n} - e) \cdot \pi \cdot L \cdot \Delta p}{1000 \cdot e} = \frac{P_\mathrm{c} \cdot (SDR - 1) \cdot \pi \cdot L \cdot \Delta p}{1000}$$

Where:

- Q_V is the permeation rate in ml/day
- P_C is the permeability coefficient in (ml·mm)/(m^2·bar·day)
- d_n is the nominal diameter of the pipe in mm
- e is the wall thickness of the pipe in mm
- L is the length of the pipe in m
- Δp is the difference in partial pressure of permeate on either side of the pipe wall in bar
- SDR is the standard dimension ratio (equal to the ratio of d_n to e)

The mass flow rate (Q_m in kg/day) can be calculated from the density of the gas under the preferred conditions (ρ in kg/m^3) using the equation:

$$Q_\mathrm{m} = \frac{Q_\mathrm{V} \cdot \rho}{1\,000\,000}$$

The calculated permeation rate can be used to determine the reduction in methane permeation when some of the transported natural gas is replaced with hydrogen. It can also be used to estimate CO_2 losses during transportation for carbon capture and storage (CCS). An example of a pipe system[3] where part of the natural gas has been replaced with hydrogen is given below:

A PE pipe system (DN 110, SDR 11) of 1 km long at 20 °C is pressurised with a 10 bar(g) blend of 80% natural gas (of which 80% is methane, the rest is nitrogen and minor constituents) and 20% hydrogen. The absolute pressure of the gas mixture is

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[3] Note that the permeation rate through a pipe is the main contributor to the overall permeation of the PE pipe system. Butt fusion joints have the same material property (P_C) and wall thickness (e) and can therefore be seen as part of the pipe. Electrofusion socket fittings and electrofusion saddle fittings will increase the wall thickness locally, thus decreasing the permeation rate. For mechanical fittings, the material may be virtually impermeable (metal) or have a higher permeability coefficient than PE (e.g. rubber). However, the total surface area of the barrier in the joint is much smaller than the surface area of the pipe, and as such it makes a negligible contribution to the total permeated volume through a PE pipe system.

therefore 11 bar(a). The partial pressure of the hydrogen is thus:

$$\Delta p_{H2} = 0.2 \cdot 11 = 2.2 \text{ bar}$$

And the partial pressure of the methane is:

$$\Delta p_{CH4} = 0.8 \cdot 0.8 \cdot 11 = 7.04 \text{ bar}$$

The permeation of this pipe system will be:

$$Q_{\text{V\_H2}} = \frac{(108 \text{ to } 193)\cdot(11-1)\cdot\pi\cdot1000\cdot2.2}{1000} = 7\,464 \text{ to } 13\,339 \, \frac{\text{ml}}{\text{day}} = 7 \text{ to } 13 \text{ litres of } H_2 \text{ per day}$$

$$Q_{\text{V\_CH4}} = \frac{(10 \text{ to } 37)\cdot(11-1)\cdot\pi\cdot1000\cdot7.04}{1000} = 2\,212 \text{ to } 8\,183 \, \frac{\text{ml}}{\text{day}} = 2 \text{ to } 8 \text{ litres of } CH_4 \text{ per day}$$

At 20 °C, the density of the gas is:

$$\rho_{H2}(293.15 \text{ K}, 101.325 \text{ kPa}) = 0.0838 \text{ kg/m}^3$$

$$\rho_{CH4}(293.15 \text{ K}, 101.325 \text{ kPa}) = 0.668 \text{ kg/m}^3$$

This results in a mass flow rate of:

$$Q_{\text{m\_H2}} = \frac{(7\,464 \text{ to } 13\,339)\cdot0.0838}{1\,000\,000} = 0.000626 \text{ to } 0.001118 \, \frac{\text{kg}}{\text{day}} = 0.6 \text{ to } 1.1 \text{ grams of } H_2 \text{ per day}$$

$$Q_{\text{m\_CH4}} = \frac{(2\,212 \text{ to } 8\,183)\cdot0.668}{1\,000\,000} = 0.001477 \text{ to } 0.005466 \, \frac{\text{kg}}{\text{day}} = 1.5 \text{ to } 5.6 \text{ grams of } CH_4 \text{ per day}$$

CALCULATING THE GLOBAL WARMING POTENTIAL (GWP100)

The Global Warming Potential (GWP) quantifies the extent to which a gas contributes to global warming over a specified period, relative to the impact of carbon dioxide. It is determined by comparing the radiative forcing of a given mass of the gas to that of an equivalent mass of carbon dioxide over timeframes of 20, 100 or 500 years. This assessment takes account of the capacity of the substance to absorb and emit infrared radiation, its atmospheric lifetime and other factors that affect its global warming potential. The GWP100 is an estimation of the 100-year time-horizon Global Warming Potential. The GWP100 values for carbon dioxide, methane and hydrogen are listed in Table 5. Hydrogen itself does not directly contribute to global warming, as it cannot absorb thermal radiation. However, in the atmosphere, hydrogen prolongs the presence of other greenhouse gases (including methane and ozone) and thus indirectly contributes to global warming. Hydrogen is therefore referred to as an 'indirect greenhouse gas'. A combination of complex models is needed to determine the GWP of hydrogen.

Table 5: GWP100 of carbon dioxide, hydrogen and methane.

Gas	GWP100	Source
CO_2	1	[29]
H_2	11.6	[30]
CH_4	28	[29]

Using the GWP100 for 0.6 – 1.1 grams of H_2 per day as given in the previous example corresponds 6.96 – 12.76 grams CO_2eq per day, and 1.5 – 5.6 grams of methane per day corresponds to 42.0 – 156.8 grams CO_2eq per day.

CONCLUSION

Gas losses due to the naturally occurring, unavoidable process of permeation are quantified as the 'permeation rate' (gas volume per period of time). Estimating permeation losses requires details of the gas network, including its dimensions, the partial pressure difference and the permeability coefficient. The film and sheeting method and jacket pipe permeation methods explain the way this material characteristic coefficient is acquired. A comprehensive overview of permeability coefficients facilitates choosing a suitable one to accurately estimate the permeation rate of methane, hydrogen or carbon dioxide through a PVC, PE and PA piping system. The example explains in detail how the permeability coefficients are used to calculate the permeation rate.

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REFERENCES

[1] F. Scholten, M. Wolters, Plastic Pipes XIV, Budapest, 2008.
[2] J. Curry, M. McKinley, J. Polym. Sci., Polym. Phys. Ed., 11, pp.2209-2225, 1973.
[3] W. Moore, Physical chemistry, Prentice Hall 5th edition, 1972.
[4] Y. Lin, H. Yasuda, J. Appl. Polym. Sci., 60, pp. 2227-2238, 1996.
[5] B. Flaconnèche et al., Oil and Gas Sci. and Techn., vol. 56, pp. 261-278, 2001.
[6] Y. Naito et al., J. Polym. Sci. vol. 29 (1991), pp. 457-462.
[7] S. Jansma S. et al., Plastic Pipes Conference PPXX, Amsterdam, 2020.
[8] J. König, GUT 6789/22," DBI, 2022.
[9] S. Schütz, et al., gwf Gas+Energie, vol. 9, pp. 58-65, 2017.
[10] M. Melaina et al., Technical Report, NREL/TP-5600-51995, March 2013.
[11] S. Jansma, "Permeatie van waterstof," Kiwa Technology, 2022.
[12] M.-H. Klopffer et al., Oil & Gas Sci. Techn.,70 (2), pp.305-315.
[13] P. I. Plastic, Handbook of polyethylene Pipe, Second Edition, 2008.
[14] M. Foulc et al., WHEC 16 / 13-16 June 2006.
[15] L. K. Massey, Permeability Properties of Plastic and Elastomers, 2003.
[16] B. Flaconnèche, IIIrd MERL Conf. "Oilfield Eng. w polym., no. 6, pp.81-98, 2001.
[17] H. Huldy, "Gasdoorlatendheid van kunststoffen en rubbers," TNO, 1967.
[18] G. Villaluenga, European Polym.J. 36, pp. 1697-1702, 2000.
[19] S. v Greuningen, "H2 permeation of PVC-O pipe.." Kiwa p.p. PVC4Pipes, 2024.
[20] W. Takens, GAS, vol. vol. 95, pp. pp. 265-266, 1975, 1975.
[21] S. Pauly, Polymer Handbook - Permeability and Diffusion Data - 4th ed, 1999.
[22] M. Sadeghi et al., J of App. Polym. Sci., vol.110, pp. 1093-1098, 2008.
[23] B. Tikhomirov et al., Makromol. Chem., no. 118, pp. 177-188, 1968.
[24] E. van der Stok et al., Plastic Pipes XV, Vancouver, September 2010.
[25] F. Scholten et al., Plastic pipes XV, Vancouver, Canada, 2010.
[26] L. Merlonghi et al., Intern. J. of Hydrogen Energy, vol. 88, pp. 1463-1473, 2024.
[27] R. Ash et al., Polymer, vol. 11, pp. 421-435, 1970.
[28] M. Klopffer et al., Oil and Gas Sci. and Techn., vol. 70, 2015.
[29] IPCC, "IPCC Global Warming Potential Value," 2024.
[30] M. Sand et al. Communnications Earth Environment, Vols. 4, 203, 2023.
[31] F. Scholten et al. "CH4 H2 perm through PA and composite pipes" Kiwa, 2009.