PVC Pipes Readiness for the Hydrogen Economy

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Abstract. Clean hydrogen can be used as a feedstock or as an energy carrier, and has many potential applications in industry, transport, energy, and buildings. According to the EU Hydrogen Strategy, the existing natural gas grid can potentially be used for hydrogen transport. PVC-U and PVC-Hi have long been preferred materials for the low-pressure gas distribution grid. In the Netherlands alone, more than 80,000 km of PVC-U and PVC-Hi pipes are in use. Based on the evidence gathered over the last 20 years, PVC pipes are well suited for the safe transport of hydrogen gas. In addition to this evidence, Kiwa carried out a study commissioned by Netbeheer Nederland and PVC4Pipes to assess the mechanical suitability of installed PVC joints, and the permeation behavior of PVC pipes and joints. Excavated joints from the Dutch gas grid were subjected to a time-accelerated test of hydrogen exposure equivalent to more than 50 years of actual service and then tested on the basis of angular deflection. Hydrogen loss due to permeation was assessed by performing permeation measurements. Permeation measurements have also been run on new PVC-O pipes and joints at two different temperatures. The study concludes that PVC joints are still mechanically suitable for hydrogen distribution and the permeability of the pipes and joints meet current leak requirements. PVC pipes can therefore be used in the Dutch natural gas grid for the safe transport of hydrogen for many decades to come.

1. Introduction

Clean hydrogen can be used as a feedstock or as an energy carrier, and has many potential applications in industry, transport, energy, and buildings. According to the EU Hydrogen Strategy, the existing natural gas grid can potentially be used for hydrogen transport. In 2018 R. Hermkens et al [1] concluded that PVC is a suitable material for the distribution of hydrogen. However, the study still left some unanswered questions. As PVC-O pipes have become an industry-leading choice for a vast range of pressure pipe applications, it may be anticipated that they will also become a good option for new hydrogen networks. Experimental data on their hydrogen permeation behaviour at different temperatures are however lacking. This paper describes the results of the studies that have been performed to answer several of these questions.

Both new and used pipes and joints (DN 110 mm) consisting of impact-resistant (PVC-Hi), unplasticized (PVC-U), and orientated (PVC-O) PVC, have been used to perform this study. The excavated pipe sections and their joints used in this study had been in service in the Dutch natural gas distribution grid for many years (from 7 to 56 years).

This paper includes results from:

- Permeation measurements for used, as-received PVC-Hi and PVC-U pipes, with hydrogen at 200 mbar(g).
- Permeation measurements for new PVC-O pipes with hydrogen at 200 mbar(g) at ~8 ˚C and ~23 ˚C.
- Permeation measurements for used, as-received PVC-U and PVC-Hi straight joints tested with hydrogen at 200 mbar(g).
- Permeation measurements for a new PVC-O joint tested with hydrogen at 200 mbar(g) at ~8 ˚C and ~23 ˚C.
- Measurement of the maximum angular deflection before leakage of used, as-received joints after artificial ageing in a hydrogen environment. The joints were tested with air at 100 mbar(g).

2. Experimental

2.1. Permeation method for the pipes

The permeation rate was measured to determine how much hydrogen is emitted through the PVC pipe wall. The setup consisted of a PVC pipe surrounded with a steel jacket pipe, inside which the permeated hydrogen eventually accumulates as shown in figure 1. All tested pipes are DN 110. The hydrogen concentration inside the jacket pipe was measured at specific times using gas chromatography.

Figure 1. Sealed PVC pipe surrounded with a steel jacket pipe for the permeation measurement in a temperature-controlled room.

After an initial phase without any permeation (the breakthrough time), hydrogen starts to accumulate inside the steel jacket. A stationary permeation phase is reached later. In this phase, the hydrogen accumulation increases linearly with time. The slope of this part of the curve is used to determine the permeation rate. A typical result is shown in figure 3. The volume indicated is applicable at standard temperature and pressure (STP conditions) and note that in the example there was no significant breakthrough time.

The permeation rate is calculated for the pipe segments and corrected for the length of the pipe and the pressure in accordance with Fick's laws of diffusion [2] (in *ml* hydrogen per *day* per *meter* of pipe length at 200 mbar(g) and room temperature).

The permeability coefficient (P_C in $ml{\cdot}mm/(m^2{\cdot}day{\cdot}bar)$) for a monolayer pipe can be calculated using the thickness of the pipe (e in *mm*), the median surface area (A in m^2), the partial pressure difference (p in *bar*) and the permeation rate (or flow of the permeate) (Q in *ml/day*), as follows. Please note that a small but negligible error is made in this conversion [3], [4]:

$$P_C = \frac{Q \cdot e}{A \cdot p} \tag{1}$$

This can be rearranged to give the permeation rate:

$$Q = P_C \cdot \frac{A \cdot p}{e} \tag{2}$$

Formula (2) can be adapted to use more pipe-related parameters as described in [3], [4]:

$$Q = \frac{P_C \cdot \pi \cdot (SDR - 1) \cdot L \cdot p}{1000} \tag{3}$$

where L is the length of the pipe (in *m*) and SDR is the ratio of the pipe diameter to the wall thickness.

The absolute pressure difference (or driving force) between the inner and outer pipe wall will decrease due to the increased concentration of the accumulated gas in the steel jacket pipe. The results were corrected to take account of this decrease in absolute pressure difference. In addition, the maximum concentration of hydrogen in the accumulated gas over all measurements was 5,7%, which is sufficiently low.

The results were used to determine the permeability coefficient for each three types of PVC. The results are shown in table 1.

2.2. Permeation method for the joints

Exactly the same test setup was used for the joints (two pipes with a straight joint in between) as for the pipes alone. All tested joints were DN 110 systems. No leakage was observed for any of the joints. The permeation rate was measured in *ml* hydrogen per *day* at 200 mbar(g) at room temperature. The results are shown in table 2.

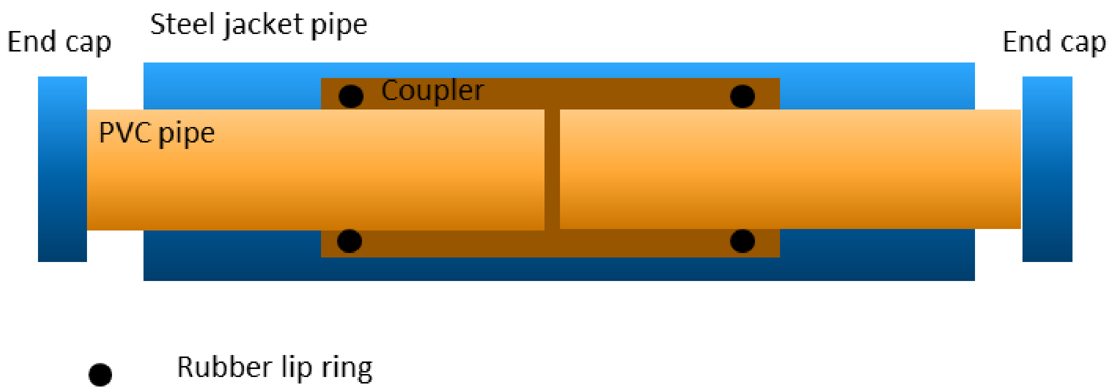

Figure 2. Schematic of the test setup.

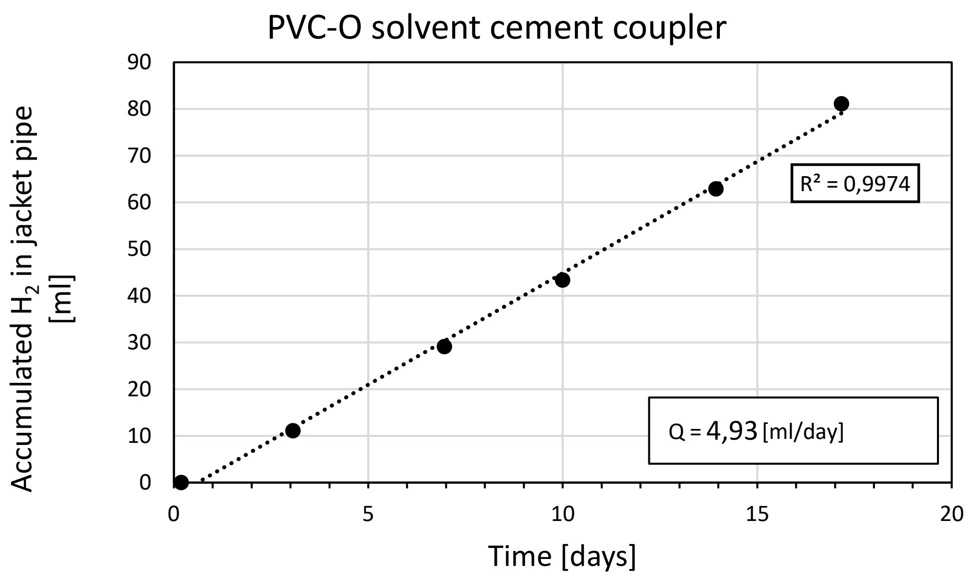

Figure 3. Typical result from the permeation experiment of a PVC-O solvent cement coupler at 23°C.

Table 1. Permeation rate at 200 mbar(g) and permeability coefficient of the different PVC pipes.

Type of PVC	Service life [years]	Temperature [°C]	Permeation rate [ml/(m·day)]	Permeability coefficient [(ml·mm)/(m^2·day·bar)]
PVC-U	53	23	12,3	90,9
PVC-U	46	23	10,3	87,3
PVC-U	14	23	11,8	115,3
PVC-Hi	27	23	11,8	117,2
PVC-Hi	7	23	17,6	181,3
PVC-Hi	27	23	11,3	113,3
PVC-Hi	21	23	16,7	119,5
PVC-Hi	23	23	15,0	116,8
PVC-O	new	23	9,7	79,7
PVC-O	new	8	5,8	47,6

Table 2. Permeation rate of the different PVC joints at 200 mbar(g).

Type of PVC	Component	Service life [years]	Temperature [°C]	Permeation rate [ml/day]
PVC-U	Injection-moulded socket fitting	unknown	23	6,5
PVC-U	Thermoformed socket fitting	56	23	7,5
PVC-Hi	Thermoformed socket fitting	42	23	7,3
PVC-Hi	Injection-moulded socket fitting	31	23	7,4
PVC-O	Solvent cement coupler	new	23	4,9
PVC-O	Solvent cement coupler	new	8	2,9

2.3. Maximum angle of deflection method

Four joints, each consisting of a socket, a rubber lip ring, and two PVC pipes, were sealed and filled with hydrogen at ~30 mbar(g). The joints were artificially aged in a temperature chamber (at 60 °C) in which the joints were stored for a period of 1000 hours.

After ageing, the joints were flushed and pressurized with air at ~30 mbar(g). Angular deflection was applied based on EN-ISO 13844 [5]. Tightness was measured continuously as the deflection increased. Instead of limiting the test to the required deflection of 2˚, the test was continued until the joints started to leak or the test rig reached its limits. The angle of deflection at which leakage occurred was recorded. The test rig as shown in figure 4 was used.

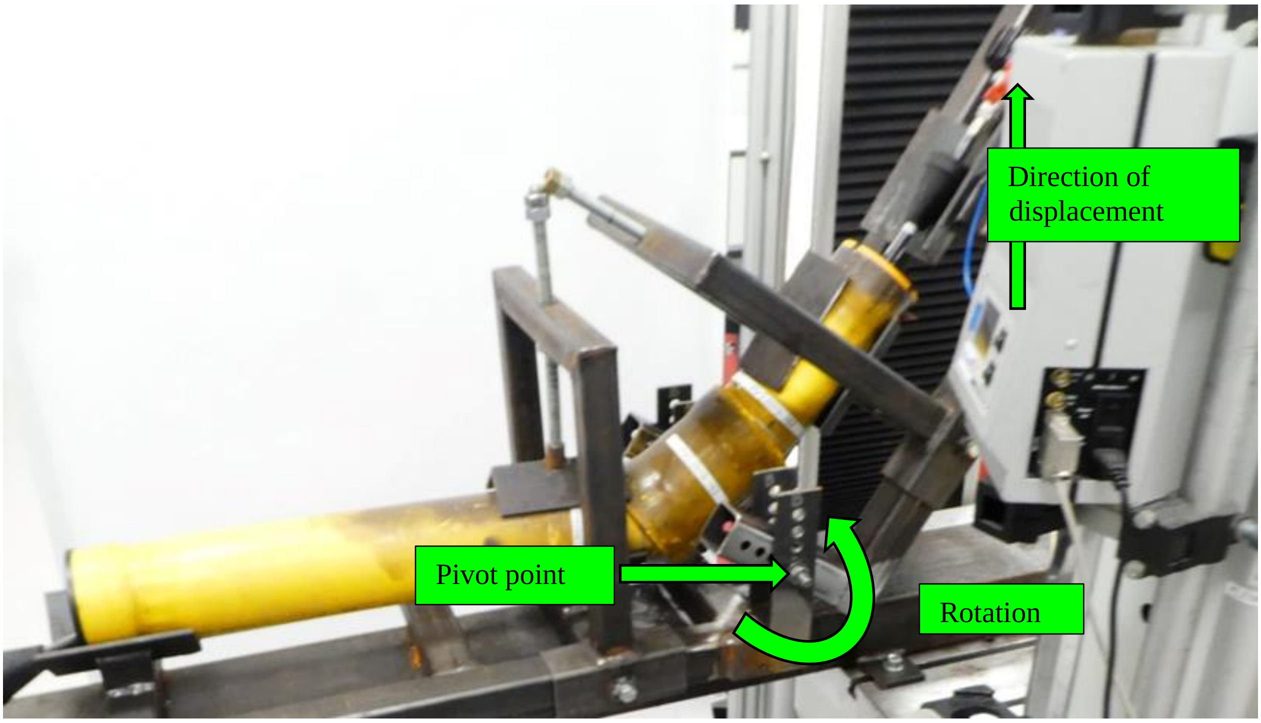

Figure 4 Angular deflection test rig (placed in a tensile test machine)

The test rig consisted of two parts, which were connected with a bolt that acted as the pivot point. The pivot point was located in the middle of the joint to introduce the rotation. The pivot location ensured that the pipes could not be pulled out of the joint, which can happen at greater angles. Depending on the diameter of the pipe and joint, the position of the bolt could be adjusted in such a way that the middle of the joint was centered on the pivot point of the test rig. The pipes (with the joint) were clamped onto the test rig in such a way that the joint could move. The test rig was placed in a tensile test machine. The tensile tester was used to apply a constant upward displacement to the movable part of the test rig. A photograph was taken at least every 30 seconds. By measuring the time between the start of the angular deflection and the moment leakage started, the picture corresponding to the moment of leakage could be selected. The measured angle of deflection in that photograph corresponded to the maximum angle of deflection before leakage occurred, see for an example figure 5. The results are shown in table 3. A maximum angle of deflection of approximately 5° for PVC-U joints after ageing with hydrogen was found. The angle of deflection of the PVC-Hi joints could not be measured as the test rig reached its maximum capability.

For comparison, another four joints were tested in the same manner without artificially ageing in hydrogen as shown in table 3.

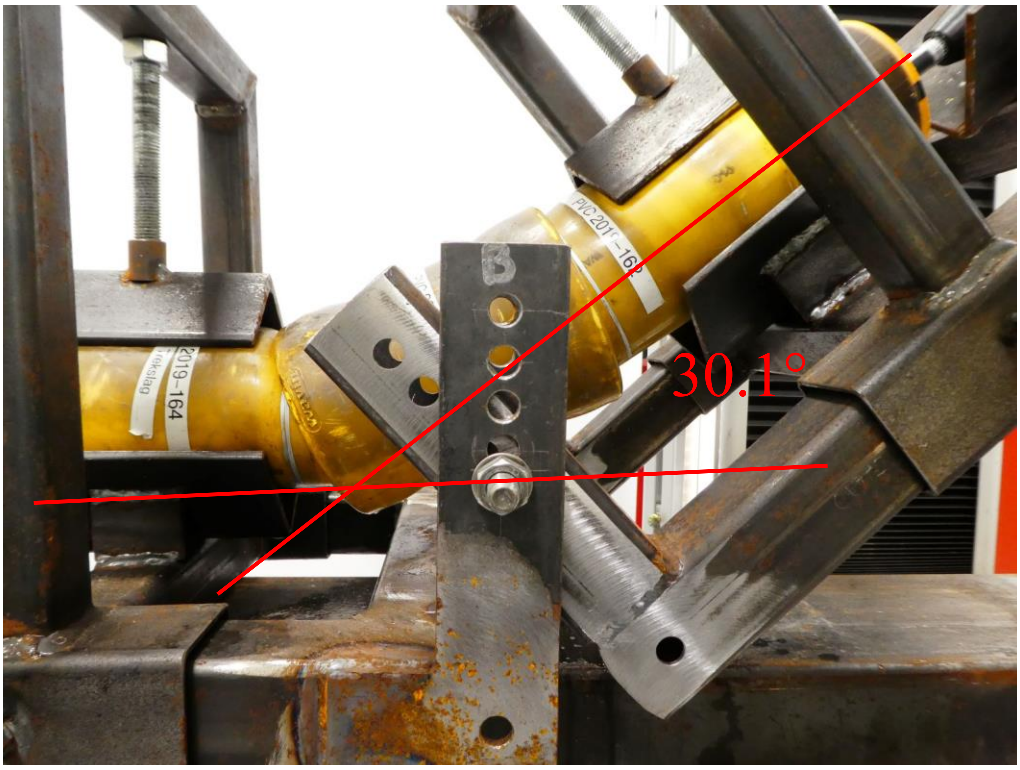

Figure 5 Maximum angle of deflection of the test rig reached where no leakage occurred.

Table 3. Maximum angle of deflection for the different PVC joints.

Type of PVC	**Component**	**Service life [years]**	**Maximum angle of deflection [°]**	**Aged (60 °C, 1000 hrs, hydrogen)**
PVC-U	Injection-moulded socket fitting	unknown	5	yes
PVC-U	Thermoformed socket fitting	56	5	yes
PVC-Hi	Thermoformed socket fitting	42	>44*	yes
PVC-Hi	Injection-moulded socket fitting	31	>30*	yes
PVC-U**	Injection-moulded socket fitting	53	12	no
PVC-U	Injection-moulded socket fitting	44	>29*	no
PVC-U	Injection-moulded socket fitting	46	>9*	no
PVC-Hi	Thermoformed socket fitting	unknown	>29*	no

*The maximum angle of deflection of several joints could not be determined as the test rig reached its maximum capability. This was partly due to pipe deformation.
**Tested joint had a diameter of 160 mm.

3. Discussion

3.1. Remarkable PVC-Hi permeability coefficient cannot be excluded

Compared to the other PVC pipes, one PVC-Hi pipe has an exceptionally high permeability coefficient of 181,3 ml·mm/(m^2·day·bar), see table 1. No explanation was found for this result. The coefficient of determination (R^2, not reported in this paper) for the permeation rate had a value of 0,997 which is considered sufficiently high and in line with the other measurements. Additionally, the impact modifier was determined to be acrylate based, the same as two other PVC-Hi pipes. The other two PVC-Hi pipes were modified using chlorinated polyethylene. With current understanding, this result cannot be explained, nor can it be excluded from the results.

3.2. Compared to the pipe, the permeation of joints is neglectable

The permeation rate of the joints at 23°C is between 4,9 and 7,5 ml/day. Compared to the permeation rate of pipes of the same length as the tested joint (~600 mm), the permeation rate is between 5,8 and 10,7 ml/day. Therefore, despite the different dimensions of the joints and the use of two rubber lip rings or solvent cement, the permeation rate is similar to that of the pipe. As such, when estimating the permeation behavior of a line pipe, one could simply relay on calculating the permeation rate of the entire line as if it were a pipe without joints.

3.3. Influence of temperature

The hydrogen permeability coefficient of PVC-O at approximately 8 ˚C is 1,7 times smaller compared to the PVC-O permeability coefficient at 23 ˚C. The resistance to permeation is thus higher at low temperatures and lower at high temperatures. The explanation for this difference can be found in the energy that the gas molecules possess. The mobility of molecules increases when the energy of the system increases. Increasing temperature is a way to increase the energy of the system and subsequently increase mobility of the molecules and the rate of permeation.

3.4. Determining the permeation rate for hypothetical real-life scenarios

The permeation rate of hydrogen through PVC lines of various designs can be calculated using the values in table 1 and table 2 and formula (2). The highest value for a certain PVC material, as given in the tables, is used for each calculation.

EXAMPLE 1

One pipe segment of 12 meters of unplasticized PVC DN250, SDR 41 pipe (A = 9,19 m^2, e = 6,10 mm) at a pressure of 100 mbar(g) (1,1 bar absolute pressure p). Over a period of one year, 70 liters of hydrogen will permeate over the full length.

$$115{,}3 \cdot \frac{9{,}19 \cdot 1{,}1}{6{,}10} \cdot \frac{365}{1000} = 70\,\frac{liters}{year}\; or\; 0{,}008\,\frac{liters}{hour}$$

EXAMPLE 2

One kilometer of impact-modified PVC DN110 SDR 41 pipe (A = 320 m^2, corrected for the pipe ends, which were still present inside the joint during testing, e = 2,68 mm) containing a joint every 12 meters at a pressure of 200 mbar(g) (1,2 bar absolute pressure p). Over a period of one year, 9707 liters of hydrogen will permeate over the full length.

$$\left(181{,}3 \cdot \frac{320 \cdot 1{,}2}{2{,}68} + \frac{1000}{12} \cdot 7{,}4\right) \cdot \frac{365}{1000} = 9707\,\frac{liters}{year}\; or\; 1{,}1\,\frac{liters}{hour}$$

EXAMPLE 3

One kilometer of orientated PVC DN110 SDR 41 pipe (A = 320 m^2, corrected for the pipe ends, which were still present inside the joint during testing, e = 2,68 mm) containing a joint every 12 meters at a pressure of 4 bar(g) (5 bar absolute pressure p). Over a period of one year, 17988 liters of hydrogen will permeate over the full length. Note that a small correction has been made to convert the test pressure of the joints to the gas pressure of the example.

$$\left(79{,}7 \cdot \frac{320 \cdot 5}{2{,}68} + \frac{1000}{12} \cdot 4{,}9 \cdot \frac{5}{1{,}2}\right) \cdot \frac{365}{1000} = 17988\,\frac{liters}{year}\; or\; 2{,}1\,\frac{liters}{hour}$$

3.5. Permeation compared to leakage

To put the measured permeation rates and the examples into perspective, the permeated hydrogen in l/h can be compared to the acceptable leak rates for gas distribution. S. Lueb proposed in [6] several maximum leak sizes for a variety of hydrogen gas distribution applications. For the main pipelines he proposed a maximum allowable leak rate of 5,0 liter per hour. For new service pipeline the maximum leak rate was 0,2 liter per hour. The highest permeated volume observed for the PVC pipes was 17,6 ml/(m·day) at 0,2 bar(g) or 0,73 ml/(m·h), which is over 272 times lower than the allowable leak rate of 0,2 l/h. Moreover, the permeated hydrogen is not concentrated at a single location but is distributed over the length of the 1 meter of pipe. Therefore, the permeation of hydrogen though a PVC pipe is much smaller than the presumed acceptable leak rate.

Hydrogen permeation will lead to the loss of energy. For comparison, 0,73 ml/(m·h) will result in an energy loss of approximately 0,0022 Wh (8 Joules) per meter of pipe per hour. This means that the energy loss due to hydrogen permeation of a kilometer of PVC pipe is approximately 2,2 Wh (8 kJ). This is the same amount as switching on an incandescent light bulb of 60 W for 2,2 minutes.

3.6. Maximum angle of deflection

The minimum angle of deflection for new PVC straight joints/sockets specified in EN-ISO 13844 [5] is at least 2°. As the joints are allowed to have two bends (one at each end), the angle of deflection should be at least 4°. This is achieved in all joints tested.

The measured values for PVC-U samples before and after ageing for 1000 hours at 60 °C and an internal pressure of 30 mbar(g) of hydrogen both fulfil the criterion of 4°. As ageing is assumed to equate to at least 50 additional years of distributing low-pressure hydrogen in practice, these results are promising for practical application.

As relatively large differences in angles of deflection were measured between PVC-U joints, some additional investigations were carried out. The exact reason for the differences in the results of the angle of deflection measurements was not found. The differences may be due to the quality of the original installation of the pipes in the socket, the ageing during use, the excavation and transport, the exposure to hydrogen during ageing or the ageing process itself (1000 hours at 60 °C), or a combination of these factors.

4. Conclusions

The permeation rate of ten PVC pipes and eight PVC joints (PVC-U, PVC-Hi and PVC-O) were determined. The permeability coefficient was also determined for each PVC pipe and all but one are comparable. These permeability coefficients can be used to calculate the permeation rate of PVC pipes in other dimensions.

The calculated permeation rate was over 272 times lower than 0,2 l/h, which is a worst-case scenario for hydrogen based on the maximum allowable leak rates for a new hydrogen service pipeline. This means that the volume of hydrogen permeating through the pipe walls is rather small and will presumably not lead to safety issues or loss of energy. The measured permeation of the joints is similar to the permeation rate of a pipe with the same length. This allows for a simplified calculation to be made to determine the permeation rate of a system by simply relying on the permeation rate of single strain of pipe without joints.

The maximum angle of deflection until leakage of eight PVC joints (both PVC-U and PVC-Hi) was determined. These eight samples were divided into two groups of joints. One group was tested as received and one group was tested after an additional ageing period of 1000 hours at 60 °C with an internal pressure of 30 mbar(g) of hydrogen. All tests showed that the maximum angle of deflection fulfils the requirements of the appropriate EN-ISO 13844 [5] standard, even after ageing. This shows that the joints can handle slight ground movements, even if used to transport hydrogen in the future.

The overall conclusion is that both unplasticized PVC and impact-resistant PVC systems used in the Netherlands show good angular deflection behavior. All PVC types (PVC-U, PVC-Hi, and PVC-O) have a low level of hydrogen permeation through the pipe wall and joints.

5. Acknowledgments

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