HyDelta 2

WP6B-1 – Safety – Gas stations

D6B.1A/ D6B.1B – Inventory, modeling and experiments related to ventilation in different types of pressure reducing stations in the distribution (low pressure) grid in the Netherlands, in natural gas and hydrogen atmospheres

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Executive summary

This research report is a follow-up to the gas stations work package from Hydelta 1.0. That study showed that for various types of gas cabinets, hydrogen more often leads to a combustible mixture at the ventilation openings than natural gas, assuming the leakage flow rates chosen in that study. This led to the recommendation to carry out additional research to identify the effects of smaller, more common leakage flow rates. It was also recommended to investigate which types of different gas cabinets are frequently used in the Netherlands. This report further develops these recommendations.

This follow-up research is important because ventilation is an important measure in the event of an unintentional gas leak. Ventilation dilutes the gas and minimizes the risk of ignition or explosion. For the transition to hydrogen, it is important to know whether these gas pressure regulating stations with the same types of gas cabinets carry the same risk with the hydrogen of application.

The aim of this study is to gain further insight into how hydrogen behaves in existing gas cabinets compared to natural gas. That insight was obtained by looking at the issue from different angles: experiments as well as simulations using finite element method (CFD). This provided interesting insights that will help policymakers determine whether, and if so what, further measures can be taken.

1e step: Inventory common types of gas cabinets
Some 55,000 gas stations are operated by district system operators (DSOs) in the Netherlands. An inventory of gas cabinets used in the Netherlands was carried out. It focused on cabinets installed by DSOs in the last 10 years, because conversion of installations to hydrogen will initially take place with relatively new cabinets and these installations are designed in accordance with NEN1059. This does not mean they are exactly the same, but they are designed with the same minimum functional requirements. Three types of gas cabinets comprise a substantial part of the total population. These are mini-gas cabinets with a volume < 0.5 m^3 (these are mostly used for a high-pressure delivery station), ½ m^3 gas cabinets and 4 m^3 gas cabinet stations.

What is a realistic leakage size?
There has been a lot of focus in this study on which leakage is representative in (normal) operation and for which leakage rate ventilation should be effective. Different sources use different assumptions to determine the expected leakage rate. This is not surprising, as leakage rates can differ due to operational pressures, maintenance or environmental factors.

This study tested both with the highest leakage rate from a recent field study (40 l/h) of more than 700 gas stations. Also, leakage flow rates were based on leakage openings in other standards (0.025 mm^2 and 0.25 mm^2). This is still a wide range of leakages where, especially for the larger leaks, it is expected to be noticed by the public coincidently in close proximity of the gas cabinet with a leak. The leaks measured the field study of more than 700 stations are considered realistic, with the largest measured leak being 40 liters per hour.

2e step: Measurements
An extensive test program was carried out with a ½ m^3 cabinet and a 4 m^3 cabinet station. With a mini-cabinet, some indicative measurements were performed to get a first impression. This was done by positioning a reference leak in the center of the cabinet during the experiments. From this, gas (hydrogen or natural gas) flows at a known flow rate controlled by a Mass Flow Controller. The gas concentration was then measured at various points in the gas cabinet, directly at the vent openings outside the gas cabinet and at a distance of about 0.5 meter away from the gas cabinet. The smallest leak selected has a flow rate of 40l/h of natural gas (125 l/h for hydrogen). The largest leak is based on a leak opening of 0.25mm^2 at a pressure of 8 bar (that is: 1.8 m^3_n /h natural gas or 5.6 m^3_n /h hydrogen). Between these extremes, several other leakage flow rates were chosen.

Key data from the experiments are shown in the three graphs below for the ½ m^3 cabinet, the 4m^3 cabinet station and the mini-cabinet where the leakage rate on the x-axis decreases in size. The first dataset on the x-axis represents both 1.8m^3_n /h natural gas and 5.6m^3_n /h hydrogen. This reasoning also applies to the other, smaller leakage flow rates.

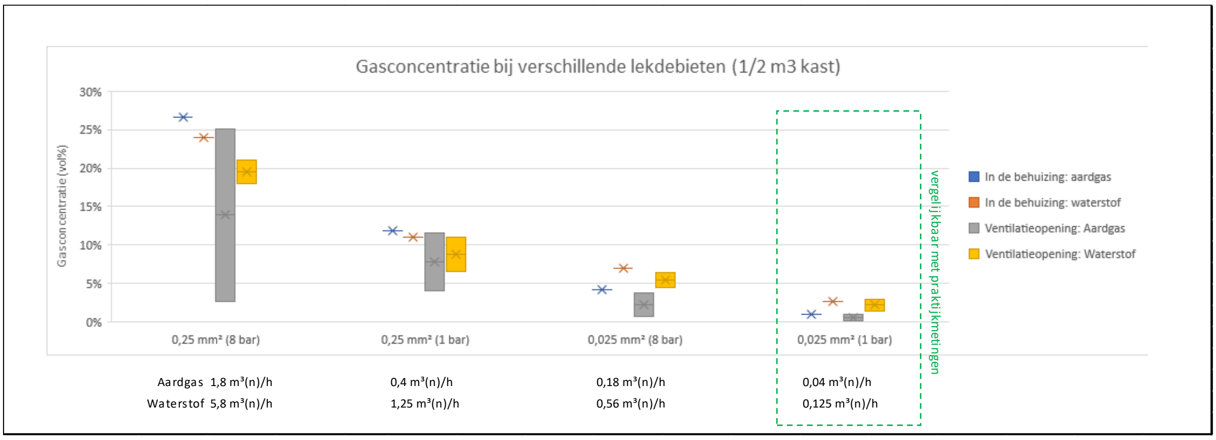

Figure 1; Gas concentration (vol%) at different leakage rates natural gas and hydrogen in a ½ m³ cabinet

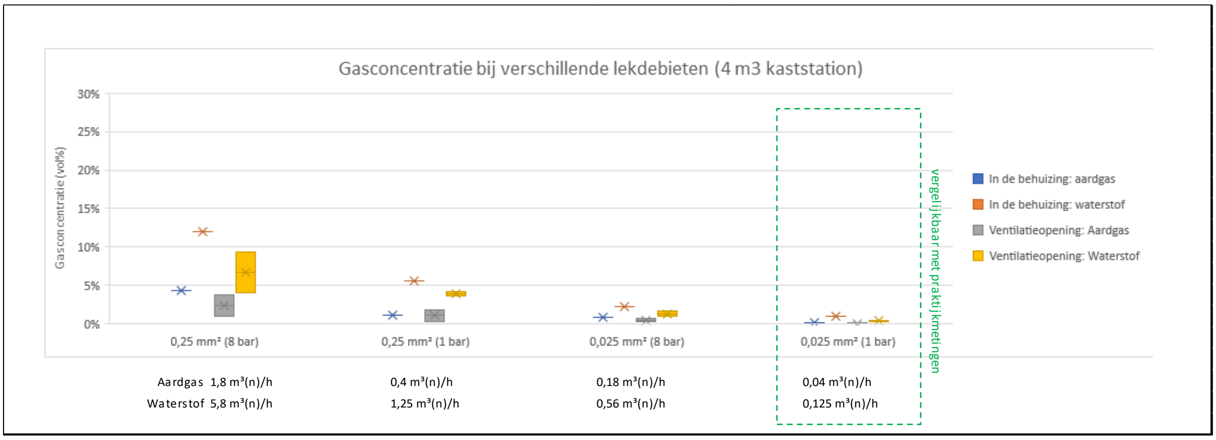

Figure 2; Gas concentration (vol%) at different leakage rates of natural gas and hydrogen at the 4 m3 cabinet station

In the case of the mini-cabinet, some indicative measurements were done to check for leakages at a leakage opening of 0.025 mm² at 8 bar pressure (i.e. 0.18 m^3_n /h natural gas or 0.56 m^3_n /h hydrogen) and 1 bar pressure (i.e. 40 l/h natural gas or 125 l/h hydrogen).

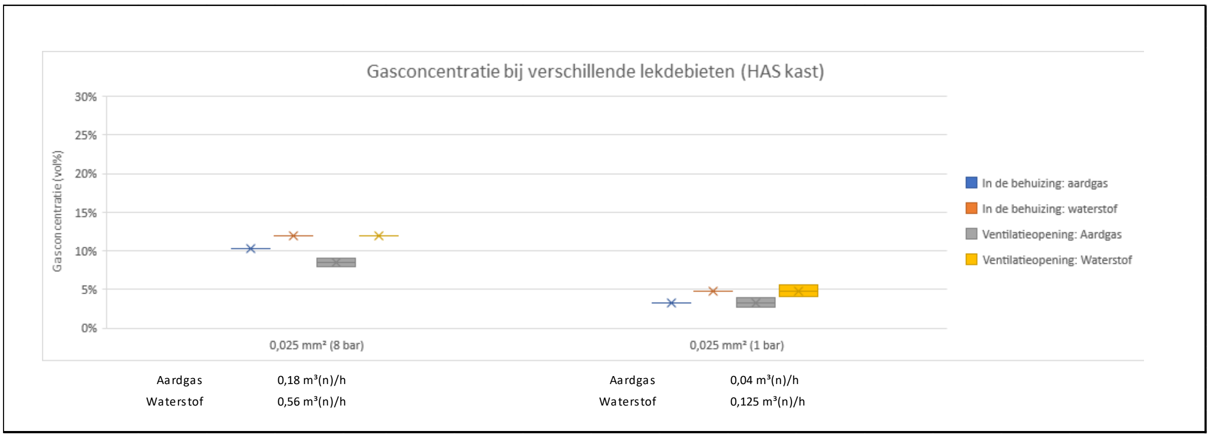

Figure 3; Gas concentration (vol%) at different leakage rates natural gas and hydrogen in a mini-cabinet

When the measurements are examined more closely, the following can be concluded:

Measurement results ½ m^3 cabinet

- For a 40l/h natural gas leak, the maximum gas concentration in a ½ m^3 cabinet is about 1 vol%, a mixture below the lower flammability limit[1] . For a similar leak for hydrogen (125l/h), the concentration rises to 2.7 vol%, which is also below the lower flammability limit. Directly at the vent openings, similar concentrations are measured, with 3.2 vol% as a local, time-dependent outlier. Half a meter away from the gas cabinet, the concentration is well below the lower flammability limit in all cases.
- Measurements with leakage openings of 0.25 mm² and 0.025 mm² measured flammable mixtures with both natural gas and hydrogen.

Measurement results 4 m^3 cabinet station

- For both natural gas (40l/h) and hydrogen (125 l/h), the concentration remains well below the lower flammability limit. The measured concentrations with hydrogen are higher, but in all cases below the limit of a combustible mixture.
- In measurements with leak openings of 0.25 mm² and 0.025 mm², no combustible mixture was measured with natural gas. In the case of hydrogen, a combustible mixture was measured at leak openings of 0.25 mm².

Measurement results mini-cabinet

- Some measurements were carried out at the mini-cabinet. These aimed to provide input to any follow-up research and are too limited to draw firm conclusions.
- An actual observation is that no combustible mixture was measured with natural gas (40l/h), while it was measured with hydrogen (125l/h).

3e step: verification with CFD calculations
As verification and to make measurements visual, CFD calculations were carried out. The aim of these modelling activities is to understand the factors affecting the flow phenomena of hydrogen gas in gas stations. Measurement data from Hydelta 1.0 were used as a reference for the mathematical models. The quality of the CFD validation is not (yet) so high that the results can be used independently of the field measurements. This is therefore an additional tool. Several reasons can be given, such as the effect of wind (variable wind) or differences in temperature (in different experiments).

The main lesson to be drawn from the CFD calculations is the influence of the roof configuration. The ventilation path is important and should facilitate the upward flow of hydrogen driven by the buoyancy. For the modelled gas cabinet with the overhanging roof lid, it can be seen that mainly hydrogen is limited to escape from the gas cabinet by a "siphon" effect. The buoyancy of hydrogen is insufficient to overcome the hydraulic resistance. An alternative CFD geometry where the overhang of the gas cabinet lid is eliminated confirms a significant improvement in ventilation.

[1] With definition as added in the glossary

Insights gained:
If hydrogen is transported using gas pressure regulating stations and the existing gas cabinets, it is expected that in case of a leakage, the concentrations in the gas cabinet will be higher than with natural gas. This study also looked at possible modifications and their effect. These are modifications that can, in principle, be carried out in the field with the existing gas cabinets. For instance, under-ventilation can be added by lifting the casing a few centimeters from its base, creating a slot at the bottom. In addition, it is possible to raise the roof edge a few millimeters by unscrewing it and replacing it with longer bolts with thicker spacers (o-rings). The effects of these practical, applicable modifications were examined. This revealed the following:

	Natural gas	**Hydrogen**
Distribution of concentrations in case of leakage	The medium mixes throughout the cabinet	There is a "blanket" effect. Concentrations are higher at the top than at the bottom.
Increase top ventilation	Lowering concentrations throughout the housing	The high concentration at the top remains high, but the blanket becomes thinner.
Effect of under-ventilation	Little effect	The thickness of the blanket decreases.
Increase top ventilation (up to 4%) + bottom ventilation (2%)	Best effect	Best effect, but less than expected. Flammable mixtures are still possible.
Adding additional ventilation effect on LEL/LFL limits	Lowering effect on all measurements	Lowering effect, but some leakage rates exceed flammability limit.

Recommendations:
The following recommendations emerge from this study:
- Consider incorporating concentration measurements into standard operating procedures by recording them for research and monitoring over longer periods. This can provide interesting insights into how populations of gas pressure regulating stations evolve.
- Consider adapting work instructions so that, when working on gas stations, technicians take a gas concentration measurement in the vent opening before opening the cabinet itself. By recording the measured gas concentration, network operators will gain more insight into actual frequency of occurrence of larger leaks with limited extra effort. In addition, leaks found can then be repaired, reducing the population of stations with leaks.
- The application of hydrogen at gas stations seems to require additional precautions to achieve the same level of safety as for natural gas. For the 4 m^3 cabinet station, this difference is more evident than for the ½ m^3 cabinet. Based on the precautionary principle, for both the ½ m^3 and the 4 m^3 cabinet station, additional precautionary measures are sensible. There are several possibilities here, such as further increasing the ventilation area of the gas cabinet, modifying the gas cabinet, placing fencing around at least one meter away from the gas cabinet or more intensive monitoring for leaks than is usual for natural gas stations.
- Further research on HAS cabinets (mini-cabinets) is recommended before HAS cabinets are converted to hydrogen. Until such research is conducted, it is advisable to apply additional precautions when distributing hydrogen.
- It is important that the standards committee of NEN 1059 makes a statement for which leakage flow rates ventilation should be an effective measure under which specific circumstances. Leakage openings and practical measurements still seem to be far apart.

Glossary

Cabinet	set-up space for a gas pressure regulation and/or metering installation
Gas pressure control and metering station	assembly of gas pressure control and/or metering installation, housing, location and associated (electrical) facilities, bounded by and including isolation valves.
Cupboard	housing with a volume (Ir) of less than or equal to 0.5 m^3 Note 1 to the term: By definition, the cabinet is considered non-accessible.
Cabinet station	housing with a volume (Ir) greater than 0.5 m^3 and less than 15 m^3 Note 1 to the term: A cabinet station can be accessible or non-accessible.
Mini-cabinet	housing with a volume (Ir) less than or equal to 0.1 m^3 Note 1 to the term: By definition, the cabinet is considered non-accessible.
Safety distance	minimum distance to be maintained between the housing of a rig or overhead components of an open rig and other objects.
Service line	pipe from the main line to the point of delivery for the benefit of the final consumer.
District Station (DS)	gas pressure control and metering station for gas pressure control of gas from high-pressure distribution network to a low-pressure distribution network.
Gas pressure control installation	device, comprising all components, including inlet and outlet piping up to and including isolation valves, which together function as gas pressure regulation and/or pressure protection.
High-pressure delivery station (HAS)	a gas pressure control and/or metering station, installed off-premises, of category A7, A8 or A9 according to NEN-1059 (2019).
m^3 at normal conditions $(m^3)_n$	quantity of gas possessing a volume of 1 m^3 in the dry state at a pressure of 101 325 Pa and a temperature of 273.15 K (0 °C).
Transfer station (OS)	gas pressure control station where gas is lowered in pressure.
Pressure control system	system that ensures that the pressure in the exhaust line is maintained within the required limits.
Net volume (Ir)	content of the set-up room minus the content of the installation.
Top ventilation/ bottom ventilation/cross ventilation	When top ventilation is used, vent openings are made at the top of a gas cabinet, allowing natural ventilation to take place. The contents of the gas cabinet can thus be refreshed. In the case of bottom ventilation, ventilation openings are provided at the bottom of the gas cabinet. In the case of cross ventilation, both top and bottom ventilation openings are provided.
ATEX	The ATEX Directive 153 (1999/92/EC and formerly ATEX 137) describes the safety requirements that employers or owners of ATEX installations are obliged to put in place so that employees can work safely and healthily in environments with a risk of explosion.

Non-hazardous area	An installation volume may be classified as a non-hazardous area (NGG) if a gas leak with an opening not exceeding 1 mm2 at the pressure prevailing under normal operating conditions, no dangerous amount of explosive gas-air mixture can produce according to NEN-1059 (2019).
Secondary hazard source	A secondary hazard source is a hazard source from which the release of a flammable substance is not likely under normal operation, and if it does occur, not frequently and only for short periods of time" (see par 5.5.2 of NPR7910-1 (2021)).
Ventilation rate (Vv)	The number of times a room's air is refreshed.
Ventilation capacity	A unit indicating the ratio of air change in a space to the volume of this space at the considered leakage rate of the hazard source present in the space.
Pressure	A force per unit area where in the SI system it is referred to as Pa or bar. Relative pressure is always a measured value relative to a reference value, usually relative to atmospheric pressure. Relative pressure can be higher or lower than that reference value, respectively over- and underpressure. To indicate the difference, the letter g (gauge) or a (absolute) is sometimes placed after the unit, so that, for example, 2 bara corresponds to 1 barg.
LEL/ LFL	LEL refers to the lower flammability limit. Below the lower flammability limit, insufficient fuel is present to sustain a combustion reaction. LEL and LFL refer to the same lower flammability limit. For hydrogen the LEL/LFL is 4 vol% hydrogen in air, for natural gas the LEL/LFL is 5 vol% natural gas in air.
UEL/ UFL	UEL refers to the upper flammability limit. Above the upper flammability limit, insufficient oxygen is present to maintain a combustion reaction. UEL and UFL refer to the same upper flammability limit. For hydrogen the UEL/UFL is 75 vol% hydrogen in air, for natural gas the UEL/UFL is 15 vol% natural gas in air.
Median	The median is the middle value of a group of numbers ranked by size. It is the number that is exactly in the middle such that 50% of the ranked numbers are above 50% and 50% are below the median.
Enhanced Tightness	Full explanation of this concept is given in NEN-EN1127-1:2019. For components with enhanced tightness, it can be assumed that no leakage can occur. These components are specifically designed for this and deviations are permanently monitored through documented periodic maintenance.
Gas cabinets	Small type: gas cabinets for HAS installation are usually located with a volume $\leq$ 0.25 m³. Medium type: housings for DS/AS stations are often located with a volume $\leq$ 0.5 m³. Large type: housings for larger DS/OS stations are often located with a volume $\leq$ 4 m³.

Content

1. Introduction

HyDelta is a national research program removing barriers that cause hydrogen projects to be delayed or even stopped. Part of the HyDelta program is the work package Gas Stations. Gas pressure regulating stations (for natural gas) are usually located in public spaces in the Netherlands. This is allowed because there is no ATEX zone outside the gas cabinet of a gas pressure regulating station. In order to be able to do so, the mechanical design shall meet the ventilation requirements and conditions set out in NEN1059: 2019. In the NEN:1059, 2019 [1], it states that with a minimum ventilation rate of more than 5 times per hour, an ATEX zone 2 applies inside the gas cabinet. Outside the gas cabinet, there is then no ATEX zoning.

The description as stated in the above standard raises all kinds of questions. What is the practical meaning of ATEX zone 2: how often may what concentration occur? What is the ventilation rate of 5 times per hour based on, and do we actually see the dilution of a leak/ the build-up of a flammable mixture reflected in measurements and models? What is the quantitative interpretation of "small" leaks and "sufficient" ventilation? And, perhaps the most important question within HyDelta's WP6B-1, in what way does hydrogen ventilate differently from natural gas from a station gas cabinet?

All these questions are interrelated. Therefore, in consultation with the expert group, it was decided not to work on the basis of a single general main question in this study. However, one objective has been formulated. The aim of this study is:

Gaining insight into the ventilation suitability of existing gas cabinets for hydrogen distribution.

To gain this understanding, the following sub-questions are addressed.

1. Sub-question 1: What are the most obvious types of gas cabinets for the application of hydrogen distribution?
2. Sub-question 2: What conditions shall be met for a gas cabinet to be suitable for hydrogen distribution? [2]
3. Sub-question 3: To what extent do the most common gas cabinets meet the conditions, with or without additional ventilation? [3]

The answer to sub-question 1 is given in section 0, to sub-question 2 in section 3.8. Sub-question 3 is answered in the conclusion (section 8).

This study can best be seen as a further development of HyDelta 1.0. This report recommended that smaller, more real-world leaks should be properly mapped. Whereas in HyDelta 1.0 (work package D1B.3A), a realistic leak size was defined using the (applicable standard) NEN 1059: 2019, namely a leak opening with a diameter of 1mm², this study substantiates that other leak openings can also (and perhaps even better) be considered realistic. Experiments are then also conducted with these leak openings. In addition, HyDelta 1.0 recommends identifying which types of gas cabinets are frequently used in the Netherlands. This study follows this recommendation.

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[2] *The requirements for ventilation of current gas cabinets are laid down in NEN1059: 2019 and NEN12186: 2014 distinguishing between different types of gas cabinets. The selected leakage opening in NEN1059: 2019 is set at 1 mm² for zoning of set-up spaces. With the results from HyDelta 1.0, this leakage opening is in question for performing the tests within this work package (for testing ventilation and establishing zoning). In HyDelta 1.0, an explicit recommendation was made that there should be a difference between an incident and a regular leak/failure.*

[3] *In this research program, the starting point for applying ventilation will first be based on existing gas cabinets and applicable standards. Modifications of the gas cabinets to improve ventilation will be determined in consultation where necessary.*

2. Overview of gas cabinets

Purpose of the inventory

To gain more insight, it is necessary to have a picture of the different gas cabinets that are frequently found in the Netherlands. In addition, the main aim of the inventory is to be able to make statements about the extent to which the tests and CFD calculations in the study are representative of the gas cabinets that are (or will be) used for hydrogen distribution. Within the study, it is possible to carry out a limited number of tests and model calculations and these should match (expected) practice as closely as possible. In addition, this part of the study provides a potentially valuable overview of the existing situation of gas cabinets for gas stations in the Netherlands.

This chapter therefore answers the following sub-question: "What are the most obvious types of gas cabinets for the application of hydrogen distribution?"

The "obvious gas cabinets" refer to gas cabinets that are now common for new natural gas stations. These are standardized and frequently used.

In consultation with the Expert Assessment Group (EAG), further interpretation of the term "obvious" has been given. Gas cabinets most likely to be used in a hydrogen network are:

- As standard as possible. This is because these are the largest numbers, allowing experience with one housing to be applied to a large number of identical specimens. Moreover, this also provides the most experience with natural gas. Finally, these are also the most mature gas cabinets.
- Housings of relatively new stations. For hydrogen projects, a grid operator will (logically) want to work with the most reliable installations and it is then unlikely that a decades-old installation will be converted from natural gas to hydrogen. This is particularly the case for pilot projects. To what extent later large-scale hydrogen distribution will also exclusively choose newer stations, with newer gas cabinets, is now an open question. For now, at least, the focus is not on older types of gas cabinets.
- Finally, an open question was posed to the EAG as to what type of gas cabinets they would select, based on their expertise, for hydrogen projects.

Approach

From helicopter view to increasing detail

Initially, an attempt was made to obtain a complete picture of all gas cabinets of stations of the DSOs. With this complete picture, it was then thought, it could be ascertained how many different types were present as "standard" in the field, with similar dimensions and mode of ventilation. This would provide knowledge of what percentage of the entire population could be designated as "standard". Additional detailed information would be requested from a number of standard gas cabinets, in particular on the exact layout of the vents. This detailed information could in turn be compared with the layout of the modelled and tested gas cabinets.

This approach has been partially successful. Network operators have been able to retrace data on all their stations. The numbers by type (HHAS, HAS, DS, OS) are known and the pressure of the stations is also known. Other data, such as dimensions of gas cabinets and manufacturers, proved to be unavailable for the entire population in many cases. In section 2.1 an overview of the gas cabinets in the Netherlands for the entire population has been presented using the available information.

Focus on the last 10 years

The focus has been on gas cabinets purchased by DSOs in the last 10 years. Of these gas cabinets, more information is available than the older gas cabinets and they are also more likely to be used for hydrogen distribution. Of these gas cabinets requested and partly received: material, manufacture and % of total procurement. In section 2.2 is an overview of the gas cabinets as purchased by the grid operators in the last 10 years.

EAG expert-opinion

Finally, the EAG was asked which gas cabinet they, based on their expertise, consider obvious for application in a hydrogen distribution network.

2.1 Housings for gas pressure regulator stations in the Netherlands

The housing and gas station

There are three parties in the Netherlands that supply gas pressure regulation installations (gas stations for short) to the regional gas grid operators: gAvilar, Raak and van Voskuilen. The DSO RENDO manufactures its own gas pressure regulation installations. A gas station consists of a housing, piping and components (the filter, pressure regulators, the pressure safety device, manometers and valves). There are a limited number of manufacturers per component and also a limited number of housing manufacturers. In practice, freestanding stations (capacity ≥ 15 m^3), cabinet stations (capacity between 0.5 m^3 and 15 m^3) and cabinets (capacity ≤ 0.5 m^3) are most common. The latter category also includes the HAS plant, with a capacity of about 1/8 m^3 .

Today's gas cabinets are made of stainless steel. From the late 1970s until 2000, polyester was also common, but it proved less robust than stainless steel after ageing.

There has been a gradual increase in parties supplying the gas cabinets. Avedko has been making the gas cabinets for some time, Zador entered the market "a few years ago". At the time, this was driven by the grid operators' desire to be less dependent on one party, with cost savings as the ultimate goal. New manufacturer names have emerged in the recent survey: Quintall, Idra-tech and van Veen Deventer. These are metalworking companies.

Most common types, by function and inlet pressure

Enquiries were made as to how many stations the DSOs operate by type, by inlet pressure and by cabinet volume. The numbers by type are known exactly. For the numbers per inlet pressure and per cabinet volume content, the data are not quite complete but of sufficient quality to give a reliable estimate of the ratio. This overview is shown in **Error! Reference source not found.**.

Table 1. DSOs' gas stations anno 2022, by type and inlet pressure. This concerns only stations connected to the high-pressure network.

Station type	Total (rounded)	Grid pressure inlet side (percentage of total by station type)		
		1 bar	>1 to 4 bar	8 bar
Delivery station	10.000	8%	13%	79%
District station	10.000	5%	17%	78%
High-pressure delivery station	34.000	8%	50%	42%
Transfer station	500	0%	2%	98%

High pressure delivery stations (HAS) are the largest numbers and are mainly connected to the 4 bar or 8 bar distribution grid. Delivery stations (AS, a connection for a company) are also a large group. The capacity of an AS is a much larger range than that of a HAS with which the gas cabinets will also have a larger range. Of the population of district stations, the vast majority have a pressure of 8 bar.

Common sizes

To find out the dimensions of gas cabinets, we initially started with a classification by group. This group are: a) ≤ 0.5m^3 , b) 0.5 - 2 m^3 , c) 2 to 4 m^3 and d) larger than 4 m^3 .

In the systems of the network operators, in many cases there is no link between the dimensions of a pressure regulator station and its function. Although it is not always well recorded, many of the stations are 0.5 m3 cabinets or smaller. Larger installations used to be common, but standardization and developments have made them smaller. Transfer stations are about equally distributed in all groups in terms of size. Of the district stations and delivery stations, the dataset was not complete enough to draw conclusions from this.

2.2 Main types of gas cabinets last 10 years

Grid operators were asked which gas cabinets they have procured in the last 10 years. This gives the following overview:

Table 2. Inventory type of gas cabinets as purchased by grid operators in the last 10 years

DSO	Cabinet Type	Material cabinet	Manufacturer	Volume (m³)	% of total (per DSO)	Remarks
Coteq	kast	RVS	Avedko	0,5	57%	dimensions 1x0.5x1 m
Coteq	kaststation	RVS	Avedko	5,12	19%	dimensions 1.6x1.6x2 m
Coteq	HAS	RVS	Avedko	0,06	8%	dimensions 0.5x0.4x0.3 m
Coteq	kaststation	RVS	Avedko	4	6%	dimensions 2x1x2 m
Coteq	kaststation	RVS	Avedko	1	5%	dimensions 1x1x1 m
Coteq	kast	RVS	Zador	0,5	4%	dimensions 1x0.5x1 m
Enexis	kast	RVS	Zador	0,5	60%	numbers is 2021 en 2022 t/m 19-10
Enexis	kaststation	RVS	Zador	4	18%	numbers is 2021 en 2022 t/m 19-10
Enexis	kaststation	RVS	Zador	1	14%	numbers is 2021 en 2022 t/m 19-10
Enexis	kaststation	RVS	Zador	2,25	8%	numbers is 2021 en 2022 t/m 19-10
Liander	kast	RVS	Zador		41%	volume 0,25 t/m 0,5 m3
Liander	kast	RVS	Adedko		12%	volume 0,25 t/m 0,5 m3
Liander	kaststation	RVS	Zador		8%	volume 1 tot 15 m3
Liander	kaststations	RVS	Adedko		6%	volume 1 tot 15 m3
Liander	kaststations	RVS	Idra-tech		3%	volume 1 tot 15 m3
Liander	kast	RVS	Voskuilen		3%	volume 0,25 t/m 0,5 m3
Liander	vrijstaand gebouw	steen	Mavo		3%	volume > 15m3
Liander	kast	RVS	unknown		2%	volume 0,25 t/m 0,5 m3
Liander	kast	RVS	Idra-tech		2%	volume 0,25 t/m 0,5 m3
Liander	vrijstaand gebouw	steen	unknown		2%	Amsterdam. Volume > 15m3
RENDO	Mini kast	RVS	Avedko	0,07	44%	To replace polyester cabinet. Rendo has relatively many mini cabinets and relatively many have been replaced in the last 10 years. Therefore possibly insufficient overview.
RENDO	kast	RVS	Avedko	0,5	32%	concerns in particular replacement polyester cabinets
RENDO	kaststation	RVS	Avedko	4	24%	concerns in particular replacement polyester cabinet stations
Stedin	kast	RVS	Avedko	0,5	48%	
Stedin	maatwerk	RVS	Avedko		31%	> 0,5 m³ en < 15 m³
Stedin	kleine kast	RVS	Avedko		18%	< 0,5 m³
Westland	unknown	aluminium	Quintall	0,5	36%	
Westland	unknown	aluminium	Quintall	0,1	31%	dimensions: 690x500x300 mm
Westland	unknown	RVS	Avedko	0,12	28%	dimensions: 565x650x330 mm
Westland	unknown	unknown	Weva	0,25	4%	
Westland	unknown	RVS	Avedko	0,5	0.7%	
Westland	unknown	RVS	Avedko	0,5	0.1%	

This shows that even in the last 10 years, Avedko has been the main party to supply station housing. Stainless steel is the most commonly used material. Polyester is no longer used in new gas cabinets, aluminium is. Advantages of aluminium over stainless steel are lower price and weight. Incidentally, the sheet material used for station ventilation makes no difference.

Furthermore, it can be seen from the data that the majority of gas cabinets installed in the last 10 years have a relatively small capacity, as summarized in Table 2.

Table 3. Percentage of gas cabinets in the last 10 years with a volume of ≤ 0.5 m³

DSO	≤ 0,5 m³
Coteq	69%
Enexis	60%
Liander	60%
Rendo	76%
Stedin	66%
Westland	100%

2.3 Expert opinion obvious gas cabinets

Analysis of the key data obtained from the query on the five to 10 most frequently used gas cabinets showed that there are many different types of "standard" sizes in circulation. As mentioned, the focus was mainly on the most frequently used gas cabinets over the past 10 years. The standards and details for each type of station are summarized below.

Common sizes

Mini-cabinet / HAS / AS

Almost all grid operators have their own "standard" dimensions for gas cabinets. For the smallest gas cabinet type, the following dimensions were given as common gas cabinets:

Table 4. Common typical dimensions of smallest gas cabinet types by grid operator.

DSO	Length (m)	Width (m)	Height (m)	Total (m³)
Coteq	0,5	0,4	0,3	0,06
Enexis[4]	0,415	0,3	0,5	0,062
Liander	0,6	0,3	0,6	0,108
Rendo	0,45	0,25	0,65	0,073
Stedin[5]	0,8	0,35	0,4	0,14
Westland	0,3	0,5	0,7	0,105

The housing capacity varies between 60 liters and 108 liters. As these are already the "most common" types, it cannot be ruled out that even smaller or larger mini-cabinets can be found in the field. However, it can be said that all grid operators are striving for standardization. Especially when looking at gas cabinets from the last 10 years, it can be said that every grid operator has a standard model. Liander has mainly installed mini-cabinets with dimensions of 0.6 x 0.6 x 0.3 meters over the past 10 years. Enexis reports that for mini-cabinets (HAS) and delivery stations are generally supplied in "virtually" the same gas cabinets. This picture is confirmed by all grid operators involved.

[4] *Detail drawing supplied with dimensions 0.5/0.4/0.3 m*
[5] *Brochure gAvilar supplied with sizes 0.75/0.45/0.75 m*

Principle of ventilation

The grid operators provided photos and drawings of the gas cabinets, see figure 4. In addition, one mini-gas cabinet was supplied for testing (more on this in chapter 5).

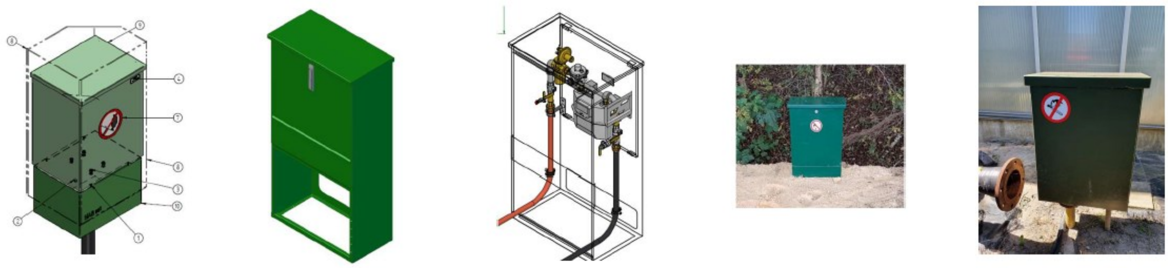


Figure 4. Common dimensions of mini-cabinets

Examination of these drawings reveals that ventilation is broadly based on four different methods, with option 3 being used by one grid operator and option 4 being a curiosity. The principles involved are::

1. Top ventilation[6] through oversized roof. We see this in the drawings of Liander, Stedin and Rendo. The roof is some distance (order of magnitude 1 cm) above the rest of the gas cabinet. The roof rests on a few screws. The roof is oversized, meaning that the roof edge is a few millimeters wider and/or longer. To avoid a completely open space (with the risk of throwing things inside), the eaves have vertical strips. Liander's drawing shows that the roof edge is larger than the base on three sides (1x long, 2x short). Stedin's drawing is less clear, but here the eaves appear to be oversized on all four sides.
2. Top ventilation by slot. The mini gas cabinet provided by Enexis features one slot on one long side, see figure 5. Again, a raised strip has been used to prevent a completely open space.
3. Westland's gas cabinets feature top and bottom ventilation. The mini gas cabinet rests on the gas-carrying pipes and there are two openings in the bottom plate. In addition, both the short sides of the roof have gaps due to the oversized roof. Westland also has a polyester (0.25 m^3) mini-cabinet that is completely open at the bottom and placed several centimeters above ground level, figure 7.
4. During a progress meeting, a picture was shown of mini-cabinets with a round ventilation grid. This is considered a curiosity and at the same time a possible solution direction when additional ventilation needs to be implemented.

[6] *When top ventilation is used, vents are made at the top of a gas cabinet, allowing natural ventilation to take place. The contents of the gas cabinet can thus be refreshed. In the case of bottom ventilation, ventilation openings are provided at the bottom of the gas cabinet. In the case of cross ventilation, both top and bottom ventilation openings are provided.*

Figure 5. Enexis mini-cabinet with single slot.

Figure 6. Cross ventilation in Westland's 0.1 m³ mini-cabinet

Figure 7. Westland's "open" 1/4 m³ polyester cabinet.

½ m³ cabinet

All grid operators indicated that the "½ m³ cabinet" is widely used. A commonly used ½ m³ cabinet from gAvilar (type DS1) has dimensions of 1.0 x 0.5 x 1.0 meters (l x w x h). Zador's ½m³ cabinet (as used by Liander, among others), has dimensions of 1.05 x 0.56 x 1 meter. Because when determining the capacity of a substation, the space occupied by the installation is *not* taken into account, the term ½m³ cabinet is still used here. Both are widely used. All ½ m^3 cabinets whose drawings we have seen use the oversized roof and top ventilation.

The roof of this housing is located a few millimeters above the top of the base. The roof rests on O-rings around the fixing bolt, as can be seen from this picture (figure 8) taken from the inside of the gas cabinet.

Figure 8. Roof (top) of 1/2 m3 cabinet, fixed with bolt on base. The gap is in connection with the outside air.

The standard principle of a ½ m^3 cabinet is that of a tilting or folding cabinet, as shown in figure 9. The tilting part of the cabinet rests on a rubber strip, so all ventilation openings are also located around the roof in the case of a folding cabinet. It is known that not all ½ m^3 cabinets are also folding cabinets, but as this does not seem to affect ventilation, no further investigation was carried out into the distribution of folding/fixed cabinet in the case of the ½ m^3 cabinets.

All ½ m3 units delivered in the last 10 years have a flat roof. ½ m^3 units with a pointed roof may be available, but these are older models. Use of these older and different cabinets for hydrogen projects is not obvious and they are therefore not considered further in this study.

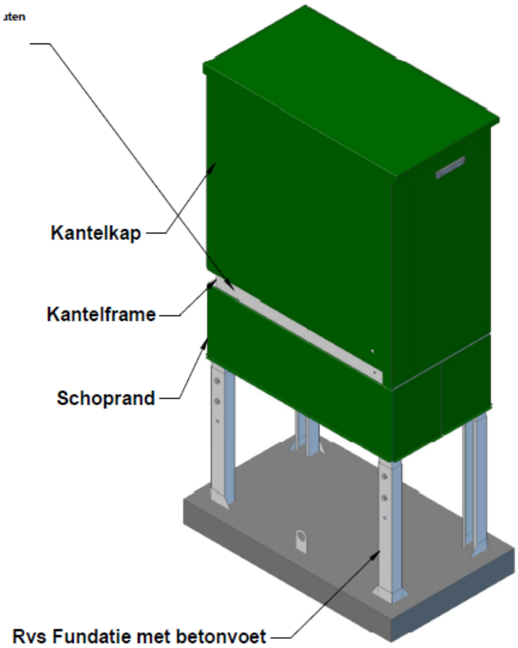


Figure 9. Drawing 1/2 m3 cabinet Liander (Zador)

Larger than ½ m^3

Another common size are closet stations measuring 2 x 1 x 2 meters. Otherwise, all kinds of sizes are in circulation. A drawing was obtained from Liander of the $4m^3$ cabinet as manufactured by Zador, (figure 10). Here, too, the oversized eaves as a ventilation principle can be clearly seen.

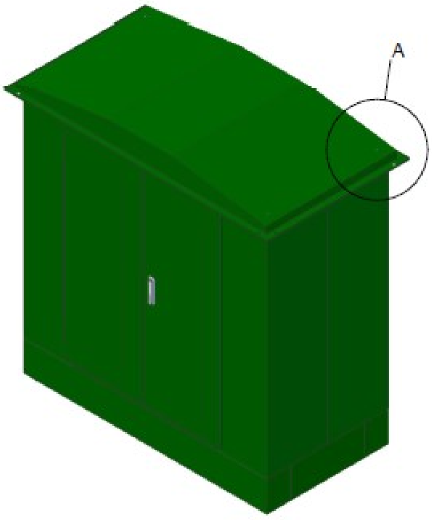


Figure 10. Cutaway construction drawing 4 m3 cabinet station Liander (Zador)

What else stands out in this drawing is that this gas cabinet does not have a flat roof, but (to some extent) a pointed roof. We see that type of roof in several places. It is in use by Rendo (figure 11), Westland Infra (figure 12) and is also present in the gas cabinet used in this study and provided by Enexis (figure 13).

Figure 11. A 4 m3 cabinet station of Rendo

Figure 12. A 4 m3 cabinet station of Westland Infra

Figure 13. The 4 m3 cabinet station as used for testing (provided by Enexis)

The reason this "gabled roof" is mentioned here is that it is suspected to affect ventilation. This is discussed in section 6.4 further consideration.

2.4 Interpretation of the inventory

A number of conclusions can be drawn from the inventory.

General:

- Gas cabinets are mainly made of stainless steel and mainly by Avedko and Zador, although other metalworking companies also supply gas cabinets.

Mini-cabinets:

- Each grid operator has its own standard mini-cabinet.
- Various methods are chosen as the ventilation principle, with the oversized roof being the most common solution.

0.5 m3 and 4 m3 cabinets

- Gas cabinets are standardized to a large extent. However, different drawings are in circulation and gas cabinets are supplied by various suppliers.
- The photos and drawings obtained show one principle of ventilation in each case: the oversized roof. Other principles of ventilation (e.g. with grilles or cross ventilation) are hardly applied.

2.5 Selection of gas cabinets and how representative they are (answering sub-question 1)

Chapter 1 posed the following sub-question:

What are the most obvious types of gas cabinets for hydrogen distribution applications?

In the last 10 years, mainly smaller gas cabinets have been installed, these gas cabinets are fairly uniform. In particular, 0.5m³ gas cabinets and 4m³ gas cabinet stations are largely comparable. With this, it is plausible that the results from this study are a good indication for all stations with this content size, as long as they are similar with regard to the method of ventilation and the ventilation area. Mini-cabinets (volume < 0.5 m³) are uniform to a lesser extent. Each grid operator has its own standard which sometimes differs a lot and sometimes little from the standard of other grid operators.

These three types of gas cabinets (the mini gas cabinet, the ½ m³ gas cabinet and the 4 m³ gas cabinet) can be used as indicative of a substantial proportion of the entire population. These three types are considered the most obvious to investigate for application with hydrogen due to their prevalence.

The *mini-cabinet* is used in a high-pressure delivery station (HAS). In absolute numbers, this is the most common gas station. In addition, given its limited volume, this cabinet will quickly reach high gas concentrations in the event of a relatively small leak. Within the project, choices had to be made as to which gas cabinets could be tested and which could not. For a long time in the project, the starting point was to choose to work out the 1/2m3 cabinet and the 4m3 cabinet station, leaving out the mini-cabinet. Reasons for excluding this option at the moment were:

- No hydrogen (pilot) projects using mini-cabinets are ongoing or in planning at most grid operators.
- Testing and modelling were likely to provide few insights. Extrapolation of data from tests with the ½ m3 cabinet from HyDelta 1.0 and initial tests in this HyDelta 2.0 study gave an indication that ventilation with the current layout of the smaller mini-cabinets could be completely inadequate.
- Given the greater diversity of mini-cabinets, the survey would have to be quite comprehensive. In doing so, too many other areas of interest would have to be removed from the survey.

Towards the end of the project, it was still decided to carry out some tests with the mini-cabinet. The aim was to gain some preliminary knowledge of the ventilation behaviour of mini-cabinets so that any follow-up research focusing on the mini-cabinet could be designed as effectively as possible. The mini-cabinet under investigation (HAS) has article number 74025, type A, and was manufactured by the company RAAK. The gas cabinet was made by “Van Veen metal Productie Deventer”. Its dimensions are 40.7 x 30.8 x 51.4 cm (lbh). There is a ventilation slot on one long side, directly under the roof edge. The ventilation slot is 13.5 mm by 404 mm, making the ventilation 4.6% of the floor area.

The *½ m³ cabinet* has been mentioned by all grid operators as an interesting type. This model is the most standardized of all sizes. Moreover, in HyDelta 1.0, a ½ m3 cabinet was also tested, which meant that results from HyDelta 1.0 could be linked to 2.0. The ½ m3 cabinet tested is a folding cabinet supplied by Enexis. Dimensions of this cabinet are 106 x 55.5 x 106 cm (lxwxh). The downward lip of the roof edge has a height of 5 cm. Top ventilation has been added on three sides, on the two long sides and one short side. The gap under the roof is 4mm. This makes the total area of ventilation 2% of the floor area.

The 4 *m^3 cabinet* was also mentioned by most grid operators as an interesting type. Of the cabinet stations "larger than ½ m^3", the 4m3 cabinet station is the most standardized. Possibly, measurements and calculations on the 4m^3 cabinet can serve as an indication for all "larger" cabinet stations. Again, it was also tested in HyDelta 1.0, so results from HyDelta 1.0 could be linked to 2.0. The dimensions of this cabinet station are 200x100x200 cm. The dimensions correspond to Avedko article number 014.30.01. Around the entire perimeter of the station there is a ventilation slot of 16mm. The total ventilation area is therefore 4.8% of the floor area.

3. Consideration of leakage opening and relevant standards

3.1 Review of research HyDelta 1.0 (work package D1B.3A)

During the launch of the HyDelta study in 2020, as part of work package 1B "gas stations", the ventilation of gas cabinets for gas pressure regulating stations was examined, among other things [2]. If gas pressure regulating stations are going to be used for hydrogen distribution, the currently applicable standards and requirements need to be reviewed.

The question at the time was twofold and formulated as follows;

1. *Are gas cabinet modifications needed for safe use with hydrogen, and if so, which ones?*
2. *Can a flammable or explosive natural gas or hydrogen mixture occur under normal conditions outside the cabinet?*

These main questions were answered through examination of these sub-questions:

1. *What is the maximum leakage rate at a station to be considered in the field during normal operating conditions?*
2. *Does the inside of the station indeed meet ATEX zoning 2, at the currently applied ventilation and maximum leakage rate, for both natural gas and hydrogen?*
3. *Is there a combustible mixture **outside the gas cabinet** at the current applied ventilation and maximum leakage rate, for both natural gas and hydrogen?*

The results showed that the selected leak opening of 1 mm² led to significant leakage flow rates where both natural gas and hydrogen concentrations rose well into the ignitable range. This did raise the question of the extent to which the selected leakage opening and leakage flow rates are considered realistic for a gas leak under normal operating conditions. In this regard, the 1 mm² should be considered as an incident and not a regular leak/failure.

From this, HyDelta 1.0 recommended, among other things, revisiting the results of that study. The main focus should be on what is a good estimate for realistic leakage rates for regular spills. An enumeration of realistic leakage rates is described in section 3.2, followed in section 3.3 by a choice of most realistic leakage rates that were then also applied in the experiments.

3.2 Available information on leaks

In HyDelta 1.0, the working group discussed leaks in gas pressure regulating stations at length. In this study, the choice was made to test leakages that correspond well to prevailing pressures in practice. The scope of application of gas pressure regulating stations is shown in table 1. The prevailing pressure, together with the selected leakage opening, forms the input for calculating the volumetric outflow of natural gas or hydrogen.

Table 1 - type of stations and applications

Station type	inlet pressure				exhaust pressure			
	≤ 200 mbar	1 bar	4 bar	8 bar	≤ 200 mbar	1 bar	4 bar	8 bar
Delivery station	x	x	x	x	Depending on customer requirements			
District station		x	x	x	x			
High-pressure delivery station		x	x	x	x			
Transfer station			x	x		x	x	

So the question "What is the maximum leakage flow rate in a gas pressure regulating station to be taken into account?" can only be answered properly when the maximum pressure (8 bar) and the maximum leakage opening are defined. These principles, as well as the link to practice, are necessary to answer in order to arrive at a good starting point. The size of a leakage opening is mentioned in several sources.

Information from standards
In the Netherlands, gas pressure regulating stations are designed according to NEN1059; 2019 [3], "Gas supply systems - Gas pressure control and metering stations for transport and distribution". This standard defines a leakage opening of 1 mm² for determining the zoning of an installation room. Of this value, the reference source cannot be unambiguously identified but it is suspected that this is the breathing opening of the safety valve or the failure of a bourdon spring of a manometer. The article "de Hinderwet en gasdrukregel- en meetstations " in the February 1968 issue of GAS magazine describes that the human factor plays a major role in leaks and that proper ventilation is a necessity. Early guidelines show that it cannot be ruled out that gas may flow out through an opening of about 1 mm² due to the jumping of a bourdon spring in a manometer [4]. The Hinderwet (1968) itself describes in Chapter IX that "in an enclosed arrangement, openings, larger than 1 mm, where - for example as a result of the failure of a diaphragm, bellows, bourdon tube or the operation of a safety valve - gas may flow out in dangerous quantities, shall be provided with a discharge pipe, through which such gas is discharged into the outside air at a safe place". So here we are talking about 1 mm instead of 1 mm². (nb. a circular leak with a diameter of 1 mm has an area of $\frac{1}{4} * \pi * 1^2 = 0.79$ mm²). This 1 mm^2 has been under discussion for some time, as will be explained in the next section.

In addition to NEN1059:2019, the IGEM/SR/25 Edition 2 (2010) [5], "Hazardous area classification of Natural Gas installations" can be consulted. In this standard from IGEM, the institution of gas engineers and managers, the recommendation for the consideration of natural gas leaks in gas pressure control stations is to choose a leakage opening of 0.25 mm² for secondary hazard sources at an inlet pressure of more than 100 mbar. For installations with an inlet pressure up to 100 mbar, the UK standard recommends using a leakage opening of 0.025 mm² for secondary hazard sources (section 4.4.1 of IGEM /SR/25).

In the NEN-EN-IEC-60079-10-1 (2021). [6], "Explosive atmospheres - part 10-1: classification of areas - explosive gas atmospheres" guidelines are set out for European ATEX regulation. In this standard applicable to explosive atmospheres in general, the same values recur for gasket leaks. In the HyDelta report "ventilation", the recommendation is provided to take measurements in the range between 0.025 mm² and 0.25 mm² where annex B of this standard (Table B.1 - "Suggested hole cross sections for secondary grade of releases") refers to "typical values for the conditions at which the release opening will not expand". This standard leaves more room for interpretation than the IGEM/SR/25 because here a bandwidth of 0.025 mm² and 0.25 mm² is given where no relationship is established with the prevailing pressure.

In the UK Health and Safety Executive's research report (RR630 - "Area classification for secondary releases from low-pressure natural gas systems") [7] defines similar values for secondary hazard sources where the content of this research report has been incorporated into IGEM/SR/25 Edition 2.

Leak size from the 1059 is up for debate
Section 7.3.11 of standard NEN 1059:2019 states a leak opening of 1 mm^2 . It states "*An apparatus room may be classified as a non-hazardous area (NGG) if a gas leak with an opening not exceeding 1 mm² at the pressure prevailing under normal operating conditions, cannot produce a dangerous amount of explosive gas-air mixture. See Annex E." Annex* E mentions that meter set-up rooms with a maximum inlet pressure of 100mbar can be classified as NGG if the conditions are met.
As already explained in the section above, this leakage hole size can be traced back to the opening at the jumping of a bourdon spring in a manometer. A second argument used in the standards committee of NEN 1059 is that 1 mm^2 is the breathing hole of a regulator. The moment a diaphragm in a regulator ruptures, an outlet opening the size of this breathing hole of about 1 mm^2 .

Within the standards committee of NEN 1059, the leakage opening of 1 mm^2 has been under discussion for some time. The vast majority of grid operator gas stations have inlet pressures of 8 bar, 4 bar or 1 bar. However, appendix E of the 1059 specifically names gas meter configurations with an inlet pressure of 100 mbar. In fact, NEN 1059 does not directly answer the question of which leakage opening should be assumed when determining the required ventilation for stations at pressures greater than 100 mbar. In the absence of this clear answer, measurements were taken within Hydelta 1.0 at a leakage opening of this 1 mm^2 , but at an operating pressure occurring in practice, namely 8 bar. The leak flow rate generated at a pressure of 8 bar and a leak opening of 1 mm^2 is much larger than what is considered realistic by experts within the standards committee for a regularly occurring leak. Such a large gas leak is both audible and smellable several meters from the gas station and will be considered an incident and not a regular leak. There is no known incident in the industry and among the members of the NEN 1059 committee that a cabinet has caught fire due to a spark from outside, under normal conditions [8]. However, gas smells are reported with some regularity at gas stations, which are responded to by the network operator's fault services.

Practical measurements of leaks at stations
To obtain a better picture of which gas concentrations actually occur at ventilation openings in district control stations, research was carried out in 2022 by Kiwa Technology, commissioned by the standards committee NEN 1059 and Netbeheer Nederland. At a total of 713 district stations, a gas concentration meter was used to take precise measurements and (according to standardized protocol) along the ventilation openings. The suction opening of the gas concentration meter was kept as close as possible to or just inside the vent opening. In this position, it was moved along the vent openings at a rate of 2 meters per minute. Another 1 minute was then measured at the spot where the maximum concentration during the circulation was measured.

No combustible mixture was found in the vent opening while taking these measurements in any case. In two-thirds of the measurements, the methane concentration is below 11 ppm. In 99.4% of all measurements, the gas concentration was below 10% LEL. Two measurements had a measured value of 10% LEL and 2 measurements are above that, with the highest measured value being 40% LEL. No combustible mixture was measured in the vent openings of all 713 stations measured. This project thus demonstrated that it is very unlikely that a gas station could be ignited from the vent openings during regular operation [8].

Leakage flow measurements from the topic of methane emissions
The project that measured the vent openings of 713 stations also received a spin-off project in 2022 from the point of view of quantifying methane emissions. Information on gas concentrations at vent openings are extremely useful from a safety perspective. From the point of view of quantifying methane emissions, it is also necessary to be able to make a statement about the size of a leakage flow rate. The technician doing the concentration measurement in the vent openings contacted Kiwa when the measured value exceeded 500 ppm. At 13 district stations, Kiwa then determined the leakage rate through a "Hi Flow Sampling" measurement. The largest leakage measured was 0.3 liters/minute (18 liters/hour). An average leak size is 2 liters/hour [9].

Leaks at gas pressure regulator stations were also investigated in Germany in 2022. DVGW research [10] revealed that regular leakages at 159 gas pressure regulator stations measured an average leakage of 1.8 liters per hour. The maximum leakage found was 31 liters per hour. It was also found that two-thirds of all measurements were less than 2 liters per hour with a median of 1 liter per hour. This average leakage (or: this emission factor) thus replaces the previously used emission factors of 25.7 liters per hour for low-pressure stations and 105.6 liters per hour for medium-pressure stations at those cited in the comprehensive study *Methane Emission Estimation Method for the Gas Distribution Grid* (MEEM [11]. The original source of these values is a 2000 study by Ruhrgas AG and is based on the small number of five measurements.

All Dutch gas grid operators are partners in the Oil & Gas Methane Partnership 2.0. This is an initiative of UNEP (United Nations Environment Program) and aims to increase the accuracy and transparency of reporting methane emissions in the oil and gas sector. Within OGMP 2.0, a distinction is made between three sources of methane emissions: fugitives (small, "normally occurring" leaks), incidents and emissions from operations. Incidents generally have a larger leakage rate than "regularly occurring leaks", but are generally reported and quickly secured. When setting a maximum leak size, it is therefore important to determine whether this should include incidents or only leak sizes that may occur more permanently.

3.3 Selected leakage opening

As already described in section 3.2, several sources were consulted to provide an unambiguous picture of leakages. For regular leakages (so-called secondary hazard sources[7]), at pressures higher than 100 mbar, it can be found that a typical leakage opening of 0.25 mm² should be selected (IGEM/HSE). A smaller leak opening of, say, 0.025 mm² might also be interesting to consider in view of the content of the European standard for explosive gas atmospheres. A leak opening of 0.025 mm² gives a leak size of 40 liters/hour at a pressure of 1 bar. Leak size measurements with the hi flow sampling method at gas stations give similar values with a maximum of 18 liters/hour (Dutch measurements) and 31 liters/hour (German measurements). A leak size of 40 liters/hour is therefore considered a realistic leak size.

In a gas pressure control station, there is a maximum pressure of 8 barg which when a leakage opening in the range between 0.025 mm² and 0.25 mm² leads to leakage flow rates of 0.18 m^3_n /h and 1.80 m^3_n /h natural gas. Previous research has examined the ratio that should be applied between natural gas and hydrogen [2] [12]. Depending on the pressure, upstream of the leakage opening, the flow is either laminar or turbulent. Also, the geometry of a leakage opening plays a role. It can be assumed that in this study a factor of 3 between natural gas and hydrogen is a logical choice based on the results from the studies cited earlier.

When this is done for the above leakage rates for natural gas, it follows that the leakage rates for hydrogen are between 0.56 m^3_n /h and 5.6 m^3_n /h.

Gas pressure regulating stations are generally used as a transition between high pressure and low(er) pressure. Here, pressures of 1 to 8 barg are applied on the high-pressure side. Therefore, the same leak openings at inlet pressures of 1 barg were also considered. This defines the following set of "relevant leak openings":

Source and notes	**Natural gas leakage rate**	**Equivalent leakage size hydrogen at same leakage openings ***
Pressure 8 bar at leakage opening 0.25 mm²	1.80 m /h^3_n	5.6 m /h^3_n
Pressure 8 bar at leakage opening 0.025 mm²	0.18 m /h^3_n	0.56 m /h^3_n
Pressure 1 bar at leakage opening 0.25 mm²	0.4 m /h^3_n	1.25 m /h^3_n
Pressure 1 bar at leakage opening 0.025 mm² For natural gas also in line with research on leakage sizes of methane emissions (maximum 40 liters/hour)	0.04 m /h^3_n	0.125 m /h^3_n

**) rounding off numbers reserved*

[7] *a secondary hazard source is a hazard source from which the release of a flammable substance is not likely under normal operation, and if it does occur, not frequently and only for short periods of time" (see section 5.5.2 of NPR7910-1 (2021))*

3.4 Leak openings and previous experiments

When the above numbers are translated into a leakage focus area, overviews can be made for both natural gas and hydrogen. When the information from HyDelta 1.0 is added, a good picture of all tests is obtained. It should be noted that selected leakage rates from HyDelta 1.0 partly overlap with leakages from HyDelta 2.0. Some leakage rates in this report are rounded up, because the setpoint of the MFC has a limited number of significant digit number positions.

When the pressure is plotted against the leakage rate (flow), several diagrams can be drawn up visualizing the "operating window". In this way, for both natural gas and hydrogen, it can be clearly seen which operating area is covered for the assumed leaks.

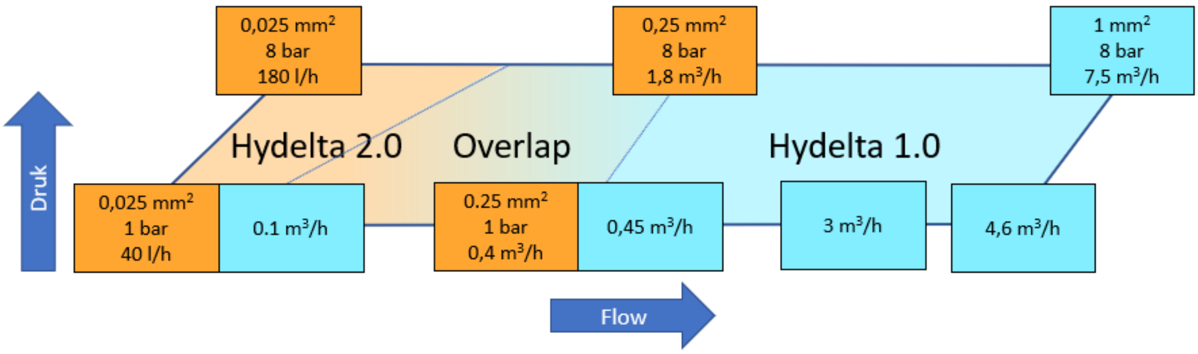


Figure 14. Selected leakage flow rates HyDelta 1.0 versus HyDelta 2.0 for natural gas

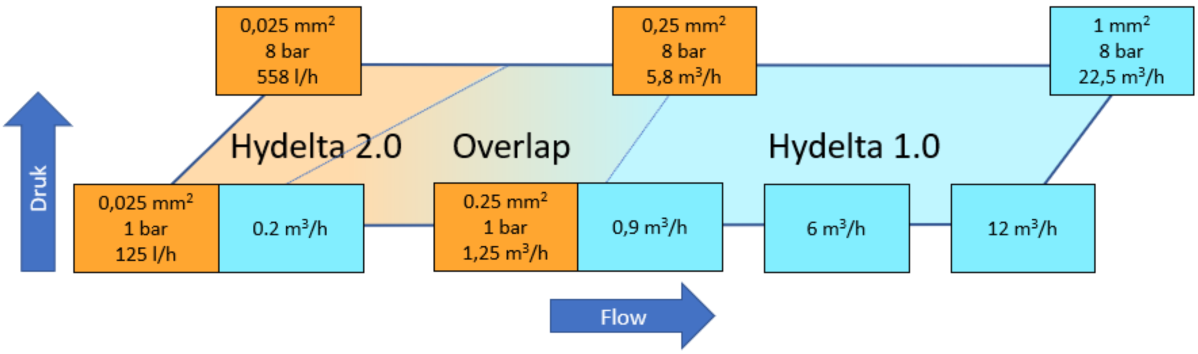


Figure 15. Selected leakage flow rates HyDelta 1.0 versus HyDelta 2.0 for hydrogen

Based on the data presented from the various studies around the area of methane emissions and the DVGW study mentioned earlier, it can be seen that the leakages found in gas pressure regulating stations approximate the smallest leakage (0.025 mm²) at the lowest proposed pressure (1 barg). It is thus reasonable to assume that a regular leakage as it occurs under normal operating conditions has been included in this test program.

The above information has been translated into a test matrix used for this study containing the two leakage openings of 0.25 and 0.025 mm². With two pressures (1 bar and 8 bar) and natural gas/hydrogen, this yields 2^3 (= 8) possible combinations. These are summarized in the table below.

Table 5. Leakage flow rates for natural gas and hydrogen. Leakage rate 1 at 8 bar pressure, leakage rate 2 at 1 bar pressure.

	Leakage rate 1 - 0.25 mm²	**Leakage rate 2 - 0.25 mm²**	**Leakage rate 1 - 0.025 mm²**	**Leakage rate 2 - 0.025 mm²**
Natural gas (m^3_n /h) *	1,8	0,40	0,18	0,04
Natural gas (g/s) *	0,42	0,09	0,04	0,01
Hydrogen (m^3_n /h) *	5,6	1,25	0,56	0,125
Hydrogen (g/s) *	0,14	0,03	0,014	0,003

**) rounding of numbers and significant figures reserved*

3.5 Why ATEX?

A gas cabinet must comply with standards that specify which leaks can still be safely mitigated and the minimum ventilation required to do so. A distinction is made here between continuous, primary and secondary release sources, which gives a picture of the origin of a leakage.

Under European directive ATEX 153, employers are legally obliged to designate ATEX zoning in areas where explosive substances are present. The risk is determined on the basis of a risk inventory and evaluation. This establishes the link with the ATEX 114 directive. The ATEX 114-approved equipment is divided into categories, indicating in which zones it may be used, so that this equipment cannot ignite an explosive atmosphere.

When distributing hydrogen, the approach is that safety is comparable to natural gas. With this in mind, (the housing of) a hydrogen gas station should also be at least as safe as (the housing of) a natural gas station. To achieve this, it must be ensured that the area freely accessible to the general public can be designated a "Non Hazardous Area (NGG)". For natural gas, within the gas cabinet of a gas station there is an ATEX Zone 2 and immediately outside the gas cabinet the "Non Hazardous Area" begins. For this reason, no fencing is normally placed around a natural gas distribution station. The same should apply to hydrogen stations. A gas cabinet (or: the gas cabinet including a shielded piece of ground surface) should be classifiable as an ATEX Zone 2. Then, immediately adjacent to this zone, no ATEX zoning is necessary and that area may be accessible to the general public.

NEN:1059, 2019 states that at a ventilation rate of more than 5 times per hour, ATEX zone 2 applies inside the gas cabinet. Then, outside the gas cabinet, no zoning applies. In the event of a small leak, sufficient ventilation should be present to properly vent out the escaping gas.

The basis of this requirement has long been established and presented in a GAS article [3]. Here, it was determined via a set of differential equations that an interrelationship between casing volume, ventilation rate and leakage rate can be established (see Appendix II).

The basis of the above standardization lies in declaring the installation technically tight according to NEN-EN 1127 Annex B (B.3 - "Enhanced tightness") or NPR-7910-1 (2021). However, because very small leaks are not immediately noticed, it is advisable to classify the inside of the gas cabinet as ATEX zoning 2 where the zone does not extend outside the gas cabinet. This way, there is no need to zone outside the gas cabinet.

We know from research that regular leaks are small and are not always noticed by the environment. However, a realistic leakage opening for a regular leakage is not explicitly named in references. Section 3.2 describes that based on recent research, it has been found that such a leakage rarely if ever exceeds 40 liters per hour [9]. Based on section 3.3, direction has been given on the size of such a leakage and this can serve as a starting point for making an ATEX calculation and establishing the corresponding ATEX zoning.

3.6 ATEX zone review according to NPR-7910-1

This Dutch Code of Practice provides informative guidance when preparing a hazard zone classification relating to gas explosion hazard. This Code of Practice serves as a practical aid for further implementation of NEN-EN-IEC60079-10-1 (2021) and should be read in conjunction with this standard.

Due to a confluence of circumstances, a leak can occur in a gas system. The leakage may be very small, so small that it is not even noticed. In the Dutch standards, a step-by-step plan has been created for this, classifying how to deal with it. First of all, if the leakage is very small (in combination with good ventilation), it can be considered whether a classification as a non-hazardous area (NGG) is possible. If this is not possible due to the amount of gas leaking in combination with available ventilation, ATEX zoning should be applied.

Annex III makes a determination of ATEX zoning for a gas pressure regulating station based on NPR-7910.

3.7 ATEX zone review according to NEN-EN-IEC60079-10-1

As mentioned earlier, NPR-7910-1 (2021) is a practical tool for the use of the NEN-EN-IEC-60079-10-1 (2021)(Explosive atmospheres - Part 10-1: Classification of areas - explosive gas atmospheres) which describes in detail the specific calculations that can be made when performing an explosion safety analysis. Here, calculations are presented which, where possible, are complemented by practical experience (or measured values) if available.

Appendices C and D of this international standard describe in steps how to perform such an analysis. A typical analysis consists of the following steps;

- ✓ Determine the type of leakage source (continuous/ primary/ secondary).
- ✓ Determine the leakage rate of the leakage source.
- ✓ Determine the degree of dilution based on leakage rate and ventilation.
- ✓ Determine the corresponding ATEX zoning based on the degree of dilution, the availability of ventilation (reliability) and the type of leak source.

Nevertheless, this method also has limitations, especially for the situation considered in this report. This study deals with very small spills from secondary hazard sources, so the graphs used to determine the degree of dilution and to determine the "circle of influence" have to be extrapolated.

Annex III uses NEN-EN-IEC60079 to make a determination of ATEX zoning for a gas pressure regulator station.

3.8 Sub-conclusion on allowed leakage opening and link to normative standards

In the introduction, the following sub-question was posed:

> Sub-question 2: What conditions must a gas station housing meet before it is suitable for hydrogen distribution?

The distribution of hydrogen must be at least as safe as the distribution of natural gas. With this, (the housing of) a hydrogen gas station must also be at least as safe as (the housing of) a natural gas station. Ultimately, this condition must be met. To achieve that, it must be possible to demonstrate that the housing (or: the housing including a shielded piece of ground surface) can be classified as an ATEX zone 2. Only then, immediately adjacent to this zone, no ATEX zoning is necessary and that area may be accessible to the general public.

To classify an area as ATEX zone 2, it must be possible to demonstrate that there is a secondary hazard source and that there is sufficient ventilation.
A secondary hazard source means that an ignitable mixture may occur in less than 0.1% of the times. To demonstrate this, knowledge of leaks occurring in practice is needed. Leaks may occur at pressure regulator stations leading to a concentration above 100% LEL, as long as they occur infrequently (< 0.1% of the time). After all, a sound maintenance regime should ensure a technically tight installation by the owner. The NPR7910-1 states, “In the event of a small leakage, sufficient ventilation should be present to properly vent out the escaping gas”. A practical interpretation of this is that the concentration should remain below the LEL/LFL. It should also be noted that when an analysis is carried out for a gas cabinet using NPR 7910-1, this only lays down a requirement that the gas cabinet should meet. Thus, the NPR 7910-1 makes no statement as to whether the built geometry of a gas cabinet is actually suitable for adequate ventilation.

The applicable standards provide several starting points for a definition of the term “small leakage”. NEN 1059: 2019 mentions a leakage opening of 1 mm². The IGEM/SR/25 mentions a leakage opening of 0.25 mm² (P > 100mbar) and 0.025 mm² (P < 100 mbar). The NEN-EN-IEC-60079-10-1 (2021) mentions a leakage opening in the range of 0.025 mm² to 0.25 mm². The moment calculations are performed on leaks of this size, it becomes clear that ATEX zone 2 is not achieved in all cases, as shown in section 3.7 and appendix III/IV.

There really is a difference between the leakage sizes mentioned in standards and those actually measured in practice. Practical measurements show that no gas concentrations above 25% LEL/LFL occur at district station vent openings. These measurements also show that leakages greater than 40 l/h have not been observed at natural gas-fueled gas stations. When this flow rate is converted (on the safe side) to hydrogen, a realistic maximum value for a leakage rate is 125 l/h hydrogen.

To gain as much insight as possible, experiments were conducted at both leakage sizes as provided in the standards and leakage sizes as they occur in practice. These are summarized in table 5 of section 3.4.

4. Approach

4.1 Broad outline of test method

As mentioned earlier, this study is best seen as a further development of HyDelta 1.0. As part of the recommendations, it was advised to research the consequences of more realistically occurring leakages. Basically, the same test set-up was used for this, so the description is also taken from the report of HyDelta 1.0.

The test setup consists of:

- Gas cylinders containing hydrogen, natural gas and nitrogen
- A gas pressure regulator and a mass flow controller (MFC).
- A standard cabinet (1/2m^3) with top ventilation only (~ 2%), supplied by Enexis.
- A standard cabinet station (4m^3) with top ventilation only (~ 4%), supplied by Enexis.
- A standard High Pressure Delivery Station (HAS)(< 0.1 m^3) with top ventilation only (~ 4%), supplied by Enexis.
- A pipe so that a leak with an outlet of 0.25 and 0.025 mm² is inserted into the gas cabinet, respectively. The leak is positioned in the center of the gas cabinet. The outflow opening also has the possibility of connecting a needle valve.

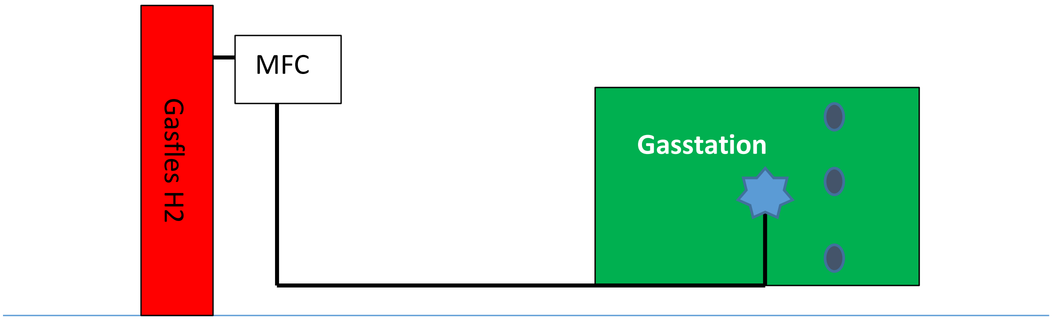


Figure 16. Schematic representation of test setup

4.2 Measuring points and measuring equipment

The natural gas or hydrogen concentration is measured at the following points:

- Inside the cabinet at 4 points (bottom, middle and 2x top). The measuring point "middle" (2), is 10 cm away from the outlet. The measurement points "bottom" (1) and "top" (3) are directly below and above the measurement point "middle", at 5 cm distance from ground level or the top of the cabinet (for the ½m3 cabinet). The measurement point "top" (4) is in the gas cabinet station at the height of the roof line, which is not the highest point. For other gas cabinets tested, the same procedure was used. Schematically, the arrangement of the measurement points is as follows;

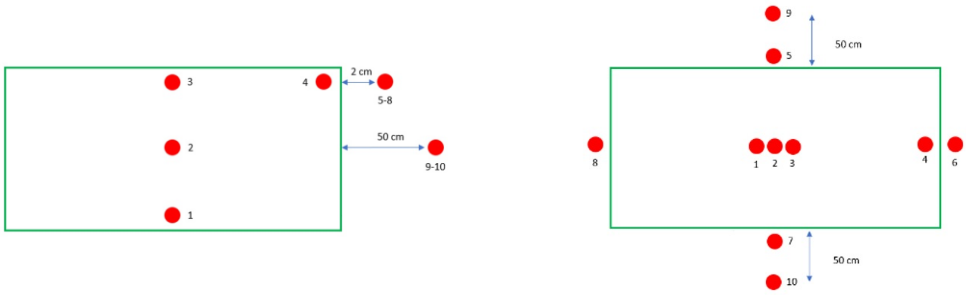


Figure 17. Setup of the measuring points in the test setup (1/2m3 cabinet), side view (left) and top view (right)

- Directly outside the cabinet at 4 points (points 5, 6, 7 and 8), all sides 2 cm away from the vent openings in the center. Riken Keiki sensors are used for this purpose, 0 – 100 vol% hydrogen. MultiRae sensors are used for experiments with natural gas. (0-100% LEL/LFL and 0-100vol%).
- Also, the natural gas or hydrogen concentration will be measured at 0.5 meters from the gas cabinet (points 9 and 10). The sensors (all MultiRae's) are placed at 1 meter above ground level. These meters contain both a ppm sensor and an LEL/LFL sensor for hydrogen.

4.3 Wind and ventilation

Wind can have a major impact on the experiments. During HyDelta 1.0, two situations were therefore created, namely an indoor situation (windless situation) and an outdoor situation. To simulate a windless situation, the cabinet station is placed in a large tent. In addition, the same series of measurements are carried out on a day that is expected to have a constant wind strength (of wind force 2 or 4) in order to limit the influence due to natural draught.

During HyDelta 2.0, the choice was made to carry out all experiments as much as possible in a windless situation where a large tent was used. When the size of the gas cabinet did not allow a tent, a sheltered situation was created using blind crowd barriers. To check whether a low-wind situation (i.e. not necessarily windless) actually existed, an indicative wind meter was used during the measurements. This was an anemometer of brand and type Skywatch OELE, with a minimum measurement range of 0.6 m/s.

NEN1059:2019 specifies a ventilation rate of 5 or greater for gas cabinets of gas pressure regulating stations. However, the ventilation rate depends on wind speed. NPR7910-1 (2021) and NEN-EN-60079-10-1 (2021) state wind speeds for calculating ventilation. The NPR7910-1 (2021) states that ventilation in which without mechanical aids the air velocity is usually higher than 2 m/s and rarely lower than 0.5 m/s. It is also described in NPR7910-1 (2021) that a wind speed of 0.5 m/s can be assumed as a guideline for calculating ventilation openings.

NEN-EN-60079-10-1 (2021) includes a table in which wind speeds are named for different situations. These values can also be used for ventilation rate analysis and correspond to NPR7910-1 (2021).

Housings for gas pressure regulating stations are located all over the Netherlands. KNMI has drawn up guidelines for average wind speed. Long-term averages (1991-2020) can be used to show how the wind varies during the months of the year. However, these measurements are normalized for a height of 10 meters above ground level to correct for global terrain roughness. The usefulness of these data for the height of gas station ventilation (0.5 meters to 2 meters above ground level) is very limited. Unfortunately, no reliable datasets are available for this height.

Wind rose figures below show that wind force changing from 1 to 5 occurs regularly. As an example, a number of wind roses have been added for weather station "de Bilt".

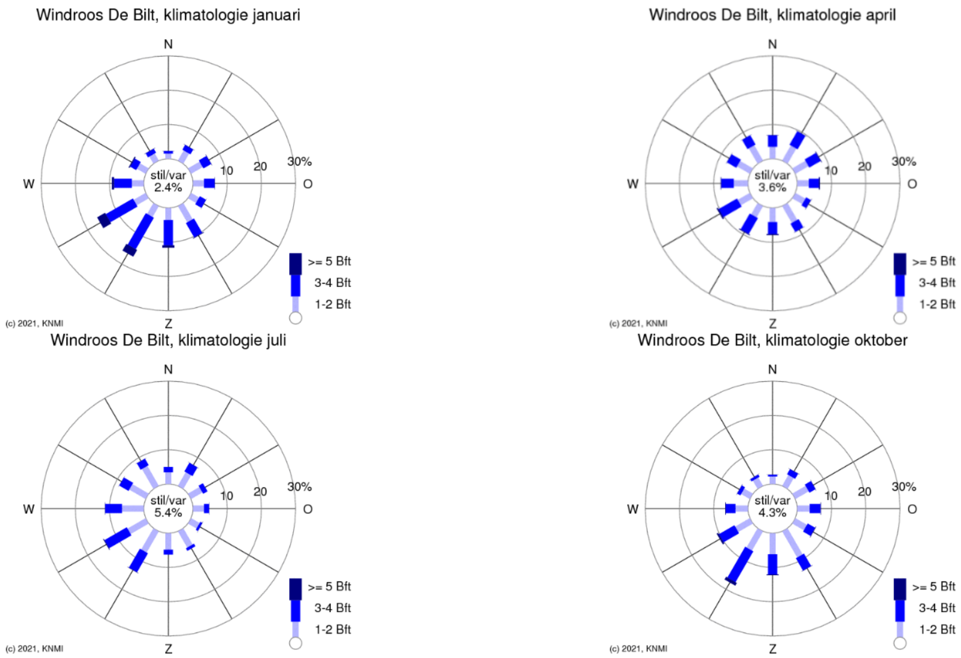


Figure 18. Wind roses during seasons in de bilt based on long-term averages

During all experiments, wind speed was measured at the gas cabinet for verification. Basically, an attempt was made to carry out all measurements on windless days. Where it is suspected that the experiments and results were affected by wind, this has been named in the report.

4.4 Photos of the set-ups

The stations were thus tested both in an outdoor situation and in an indoor/windless situation. Stations are always outdoors in practice. However, it is expected that natural ventilation at windless and/or wind-blown moments will perform less well than when there is natural ventilation by wind. In order to simulate windless and/or wind-free situations, both the 1/2m^3 cabinet and the 4m^3 cabinet station were placed in a tent.

Figure 19. The ½ m³ cabinet in a windless situation

Figure 20. The 4m³ cabinet station in a windless situation

From a gas cylinder, natural gas (L-gas) and hydrogen were added into the gas cabinet in a controlled manner using a mass flow controller (MFC), respectively. This gas flows out in the center of the gas cabinet from a leakage opening with an area of 0.25 and 0.025 mm^2 , respectively. Measurement points were installed in the gas cabinet, one at 5 cm from the bottom, one in the center, one at 5 cm from the roof line and one near a vent opening. In addition, sensors were placed on all four sides of the cabinet, measuring outside the cabinet just below the ventilation opening. Finally, sensors were placed measuring at a distance of 0.5 meters. These sensors are positioned 1 meter above the ground as shown in the photos above. In this way, the flow behaviour of the gas leak is mapped. Additional information about the test setup can be found in appendix IV.

5. Discussion results of existing gas cabinets

The two sections below present one measurement for natural gas and one measurement for hydrogen. Both tests were carried out in the 1/2m^3 cabinet at the highest pressure in a windless situation (with the smallest leakage opening). These paragraphs serve as an example of how all the results from Table 5 were processed. These results are added in Annexes VII to X of this report.

5.1 Leakage rate 0.18 m^3_n /hr - natural gas

In the first test, the smallest leakage opening in accordance with IGEM/SR/25 Edition 2 was created at a pressure of 8 bar in the ½ m^3 casing with the concentration rising to a maximum of 6.0 vol%. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

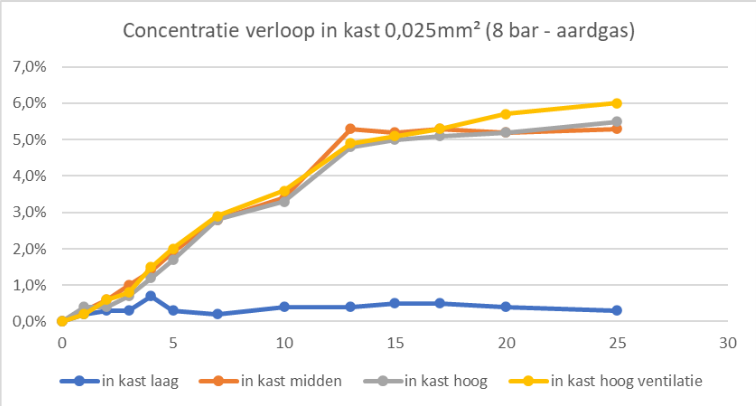


Figure 21. Concentration (vol% natural gas) in the ½ m3 cabinet at a leak of 0.025 mm² at 8 bar

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Concentration of natural gas	6.0vol%	6.0vol%	2.0vol%	0.1vol%

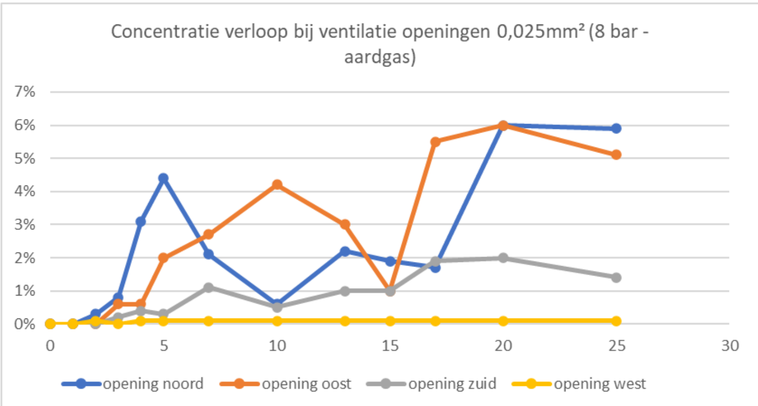


Figure 22. Concentration at the vent openings (vol% natural gas) in the ½ m³ cabinet at a leak of 0.025 mm² at 8 bar

At a distance of 0.5 meters from the housing, measurements were also made with sensors at a height of 1 meter. These have a measurement range of up to 1000 ppm and incidentally 100 ppm was reached. At a distance of 0.5 meters, no LEL/LFL values were detected.

5.2 Leakage rate 0.56 m^3_n /hr - hydrogen

When creating the defined leak with hydrogen at the same pressure, the measured leak rate was about 0.56 m^3_n /h. This leak led to a hydrogen concentration of up to 6.9 vol% in the casing.

The concentration at all measurement points in the gas cabinet stabilizes after about 10 minutes and then remains almost the same throughout the test. The graph below shows the concentration of hydrogen as a function of time in minutes.

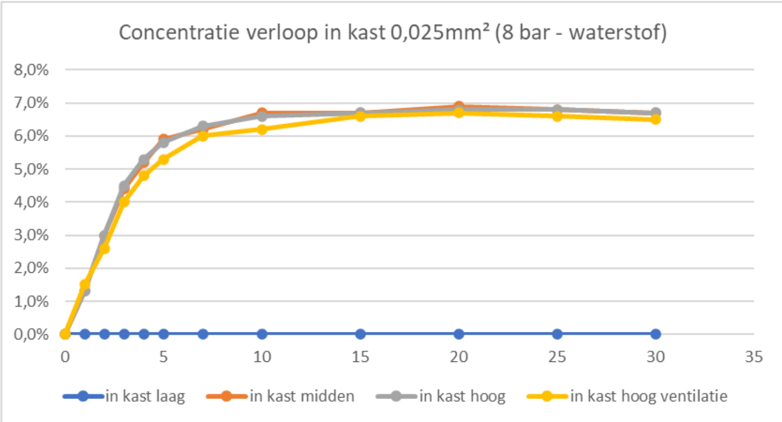


Figure 23. Concentration (vol % hydrogen) in the ½ m³ cabinet at a leak of 0.025 mm² at 8 bar

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes.

	North	East	South	West
Hydrogen concentration	6.3vol%	6.4vol%	4.5vol%	6.4vol%

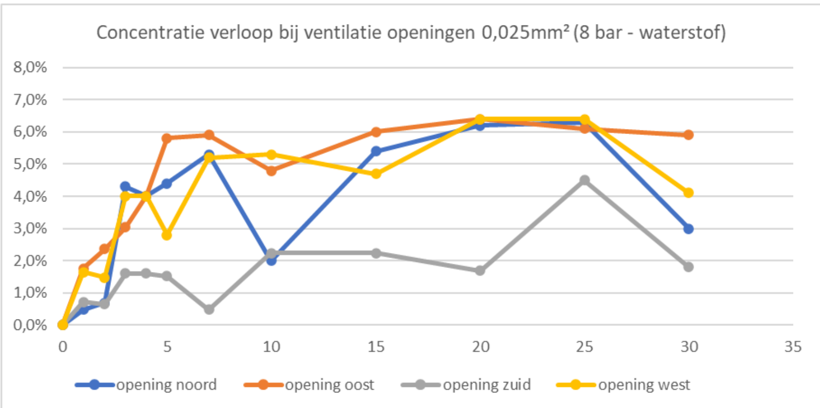


Figure 24. Concentration at the vent openings (vol% hydrogen) in the ½ m³ cabinet at a leak of 0.025mm² at 8 bar

A distance of 0.5 meters from the gas cabinet was also measured with hydrogen sensors at a height of 1 meter. These have a measurement range up to 1000 ppm and values up to 580 ppm were achieved on the west side of the gas cabinet. At a distance of 0.5 meters, no LEL/LFL values were detected.

5.3 Summary of results

The results of the test program for the different gas cabinets (the 1/2m³ gas cabinet, the 4m³ gas cabinet station and the HAS gas cabinet) are collected in Annexes VII to X. The main data of all these tests are briefly summarized in the tables below. The values in red indicate when the maximum concentration measurement falls within the flammability limits of the gas-air mixture. When a field in the tables below is not filled in, it means that no value was measured.

1/2m³ cabinet

Table 2 - 1/2m3 cabinet results - windless situation for natural gas (top) and hydrogen (bottom). LEL/LFL natural gas ≥5 vol% and LEL/LFL hydrogen ≥4 vol%. Outside the gas cabinet was measured at 0.5 m distance.

Aardgas/ natural gas		1/2m3 kast						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,179	8	6,0%	6,0%	6,0%	2,0%	0,1%	-	100
0,04	1	1,0%	1,0%	0,5%	0,1%	0,4%	-	-
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
1,8 *	8	26,6%	21,5%	25,1%	2,7%	23,1%	7,0%	>1000
0,4	1	11,9%	11,3%	11,6%	4,0%	10,8%	-	-

Waterstof/ hydrogen		1/2m3 kast						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,558	8	6,9%	6,3%	6,4%	4,5%	6,4%	-	580
0,125	1	2,7%	2,9%	2,6%	1,4%	3,2%	-	260
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
5,8	8	24,0%	20,0%	20,0%	18,0%	21,0%	18,0%	>1000
1,25	1	11,0%	10,0%	11,0%	6,5%	11,0%	-	580

*) leakage produces natural gas concentrations above the UEL/ UFL but because there will always be a transition in concentration somewhere within the flammability limits of the gas, these values are shown in red.

4m³ cabinet station

Table 3 - 4m3 cabinet station results - windless situation for natural gas (top) and hydrogen (bottom). LEL/LFL natural gas ≥5 vol% and LEL/LFL hydrogen ≥4 vol%. Outside gas cabinet was measured at 0.5 m distance.

Aardgas/ natural gas		4m3 kaststation						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,179	8	0,8%	0,2%	0,7%	0,4%	0,4%	-	-
0,04	1	0,1%	0,0%	0,0%	0,0%	0,1%	-	-
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
1,8	8	4,3%	2,6%	1,0%	3,7%	3,7%	-	-
0,4	1	1,1%	0,9%	0,3%	0,5%	1,8%	-	-

Waterstof/ hydrogen		4m3 kaststation						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,558	8	2,2%	0,9%	1,6%	1,1%	1,3%	-	70
0,125	1	1,0%	0,3%	0,4%	0,4%	0,4%	-	10
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
5,8	8	12,0%	9,1%	4,0%	9,3%	6,0%	-	570
1,25	1	5,5%	4,1%	4,0%	3,6%	4,1%	-	120

HAS cabinet

The capacity of the HAS cabinet is approximately 0.06 m³.

Table 4 - HAS cabinet results - windless situation for natural gas (top) and hydrogen (bottom). LEL/LFL natural gas ≥5 vol% and LEL/LFL hydrogen ≥4 vol%. Outside the gas cabinet was measured at 0.5 m distance.

Aardgas/ natural gas		HAS kast				
Lekopening 0,025 mm^2						
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening		op 0,5 m	
nm3/hr	bar	vol%	vol%			
			Links	Rechts	%LFL	ppm
0,179	8	10,3%	9,1%	7,9%	0,0%	0
0,04	1	3,3%	3,9%	2,7%	0,0%	0

Waterstof/ hydrogen		HAS kast				
Lekopening 0,025 mm^2						
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening		op 0,5 m	
nm3/hr	bar	vol%	vol%			
			Links	Rechts	%LFL	ppm
0,558 *	8	12,0%	12,0%	12,0%	0,0%	410
0,125	1	4,8%	5,6%	4,1%	0,0%	20

** experiment voortijdig gestopt (ivm veiligheid) door snelle opbouw van waterstof concentratie.*

5.4 Actual ventilation rate (derived from measured values)

Section 3.4 describes that the derivation of the ventilation rate was achieved via a set of differential equations describing an interrelationship between the gas cabinet volume, the ventilation rate and the leakage rate [3]. The result of this calculation is the gas concentration that can be achieved in a gas cabinet with these specific boundary conditions. As the origin of this information is considered very important for considering the topic of ventilation, a part of the article has been added in Appendix II. Namely, this establishes the ventilation rate of more than 5 (as used in NPR-7910-1 (2021)).

This reasoning can also be reversed. Using the volume of the gas cabinet, the leakage rate and the stabilized final concentration of an experiment, the ventilation rate of a specific geometry can be determined.

The graphs below show the measured concentration of natural gas (in vol%) as a function of time in minutes for 1 mm², 0.25 mm² and 0.025 mm², respectively. Here, the different measurement points cabinet low (KL), cabinet middle (KM), cabinet high (KH) and cabinet high ventilation (KHV) are plotted. In addition, a curve was calculated using theory to calculate the average gas concentration. The average gas concentration of all measurements (cabinet low (KL), cabinet middle (KM), cabinet high (KH) and cabinet high ventilation (KHV)) was also plotted.

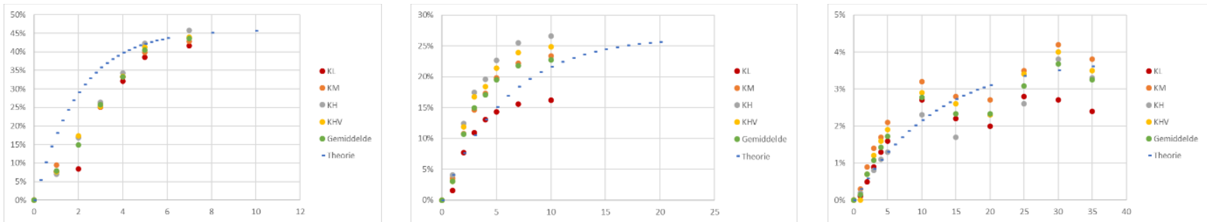


Figure 25. Natural gas concentration as a function of time (½ m³ case) for a 1 mm², 0.25 mm² and 0.025mm² leak at 8 bar

When these three measurements are considered for natural gas at 8 bar (at leakage openings of 1 mm², 0.25 mm² and 0.025 mm² respectively) in a 1/2m³ gas cabinet, we can derive the following data based on the measurements;

Table 5 - Leakage opening, leakage rate and maximum natural gas concentration

Leakage opening [mm²]	Leakage rate (m^3_n /h)	Maximum concentration (vol%)*	Ventilation rate [-]
1	7,5	45,9	25
0,25	1,8	26,6	14
0,025	0,18	6,0	12

**) maximum natural gas concentration measured inside the casing*

Thus, the ventilation rate depends on the leakage rate, cabinet geometry, cabinet volume and ambient conditions (wind/temperature). A similar conclusion has been established using previous literature [3]. For this specific geometry, the determined ventilation rate is always greater than the required ventilation rate of 5 (and thus on paper has sufficient capacity) with which it can be stated that based on the method in NPR7910-1 (2021), table 7, a ATEX zone 2 may apply.

However, it can also be stated that at a ventilation rate of more than 5, a significant gas concentration (of more than 25% LEL/LFL) can still occur in the gas cabinet. Setting the desired ventilation rate is thus not a comprehensive means of ensuring adequate ventilation for this particular gas cabinet.

6. Adjustments to the ventilation of ½ m^3 cabinet (exploratory study)

6.1 Introduction

The chapter 5 is discussed the results of tests with different leakage to standard gas cabinets with unadjusted ventilation. For the 1/2m^3 gas cabinet, only top ventilation was applied. The same applies to the 4m^3 gas cabinet station and the HAS gas cabinet.

In NEN1059:2019, Table 3 sets out what the total minimum free area of ventilation openings and/or ducts should be as a percentage of the floor area. Here it is indicated that for non-accessible cabinet stations and cabinets, both top ventilation and top and bottom ventilation may be applied. Here, the percentage of the floor area is specified where these percentages vary depending on the situation. For example, it is specified that a cabinet must have at least 2% top ventilation and that in the case of top and bottom ventilation, at least 1% per ventilation position must be maintained. Other studies [13] [14] have shown that combined top and bottom ventilation can lead to improved ventilation conditions and consequently lower gas concentrations in the event of a leak.

To gain more insight, the effect of adjusting the ventilation of the ½ m^3 cabinet was investigated. This was done in two steps. Initially, under ventilation was added (2% of the floor area). It was then continued by expanding the ventilation as far as possible within the design principle of the gas cabinet.

6.2 The effect of additional under-ventilation

This gas cabinet only has "standard" 2% top ventilation, as required by NEN1059:2019. From EAG, the desire was to minimise damage to the gas cabinet when adding additional ventilation. By placing the base of this gas cabinet on metal strips, the ventilation was adjusted from top ventilation to top and bottom ventilation. Here, 2% bottom ventilation was added, creating cross ventilation. Thus, the cabinet then has 2% top ventilation and 2% bottom ventilation.

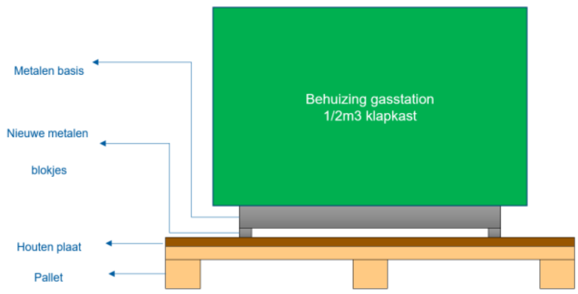


Figure 26. Custom ventilation ½ m^3 cabinet for the purpose of cross ventilation using metal strips

Successive experiments were carried out with natural gas and hydrogen with the smallest leakage at 8 bar (0.56 m^3_n /h). In previous experiments for the 1/2m3 gas cabinet, it has been observed that the maximum natural gas or hydrogen concentration in the gas cabinet is just above the LEL/LFL. It was investigated whether the additional ventilation could lead to lower concentrations.

The left graph below shows the concentration of natural gas (in vol%) as a function of time in minutes. The same experiment was carried out with hydrogen and shown in the right graph. The dashed lines are the measured values from the standard case, the solid lines from the modified case with cross ventilation. The colors of the lines and dashed lines are the same and relate to the location of the measurement point.

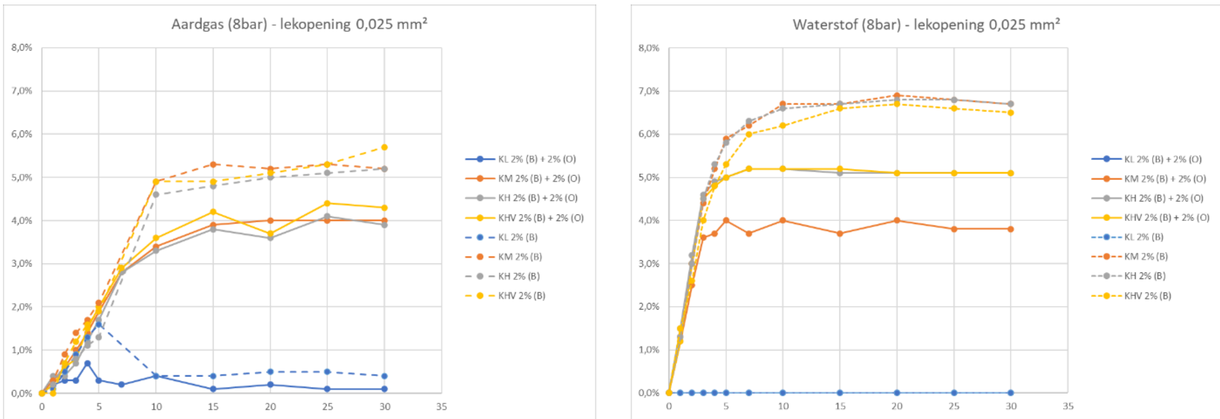


Figure 27. Concentration (vol % natural gas on the left and vol % hydrogen on the right) in the ½ m³ cabinet at a leak of 0.025 mm² at 8 bar

The graphs above show that the measured gas concentration at the "middle", "high" and "high ventilation" measurement positions is significantly lower for the combined top/bottom ventilation compared to top ventilation only. This is true for both natural gas and hydrogen. What is also noticeable is that natural gas with combined top/bottom ventilation stabilizes just below LEL/LFL level for these leakage conditions. For hydrogen with cross-ventilation, an improvement compared to the baseline can be observed, however, the concentrations of hydrogen at the measurement positions are at or just above the LEL/LFL.

Additional experiments were also carried out for hydrogen leaks with/without wind at a leakage opening of 0.025 mm² and 8 bar to capture the effects of modified ventilation and wind. For easy comparison of experiments, the average values of these measurements are shown in bar graphs. The graph below shows the average concentration of hydrogen (in vol%) for different measurement positions in the gas cabinet. The average concentration was determined in the time span between 5 and 30 minutes.

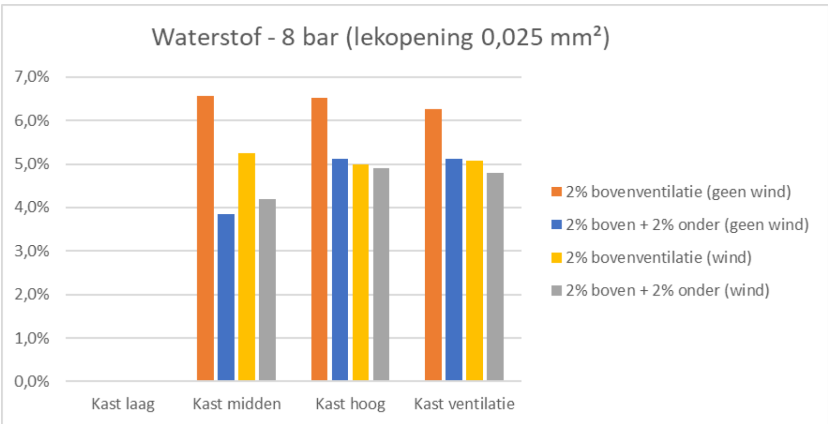


Figure 28. Concentration (vol % hydrogen) for different measurement positions in the ½ m³ cabinet

The measured average gas concentration is significantly lower at the "middle", "high" and "high ventilation" measurement positions for cross ventilation compared to top ventilation only (orange versus blue). The effect of wind is evident for both top ventilation (orange versus yellow) but less evident for cross ventilation (blue versus grey). Most measured mean values in the gas cabinet are above or just at the flammability limit.

6.3 The effect of additional top and/or bottom ventilation

Since the effect of adding 2% extra under-ventilation proved to be limited, further work was done to increase the ventilation area. This was done in a way that suited the design principle of this gas cabinet.

By adding additional rings at the top of the cabinet, the roof can be lifted further and the top ventilation can be increased. At the bottom, using the metal strip (see Figure 26) lower ventilation can be added. The top ventilation varies between 2% and 6% of the floor area. A further increase above 6% was not possible because then the gap between the gas cabinet and the downward-sloping edge would also have to be increased, and that would mean a modification that goes against the design principle of this gas cabinet. The upper ventilation of the gas cabinet can be increased to 6% with very little effort, a larger percentage would require additional efforts where the gas cabinet would have to be fitted with additional grilles, for example. The bottom ventilation varies between 0% (closed) and 2%.

Figure 29. Modification of ½ m³ cabinet with additional top and/or bottom ventilation

In this step, a number of experiments were successively carried out with natural gas and hydrogen with the smallest leakage at 8 bar (0.56 m^3_n /h) as the starting position. In previous experiments for the 1/2m³ gas cabinet, it was observed that the maximum natural gas or hydrogen concentration in the gas cabinet is just above the LEL/LFL.

This approach was elaborated in a dynamic test matrix that was discussed with the "expert assessment group" before the start of the execution of all experiments.

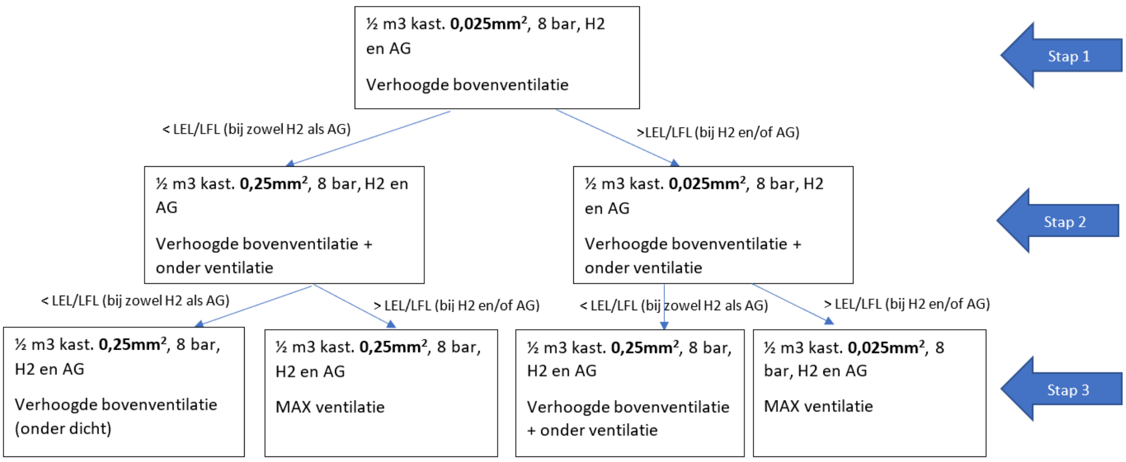


Figure 30. Design of dynamic test matrix.

After conducting the first set of experiments (step 1, indicated by a blue arrow), a choice is made between further improving the ventilation (when the measured natural gas or hydrogen concentrations are above the LEL/LFL) and increasing the leakage opening (when the measured natural gas or hydrogen concentrations are below the LEL/LFL).

Successively, as a continuation, part of the test matrix is performed in step 2 and step 3 as indicated by red boxes. These indicate the route followed and the percentage of ventilation applied in each step to maximize ventilation behavior is also named.

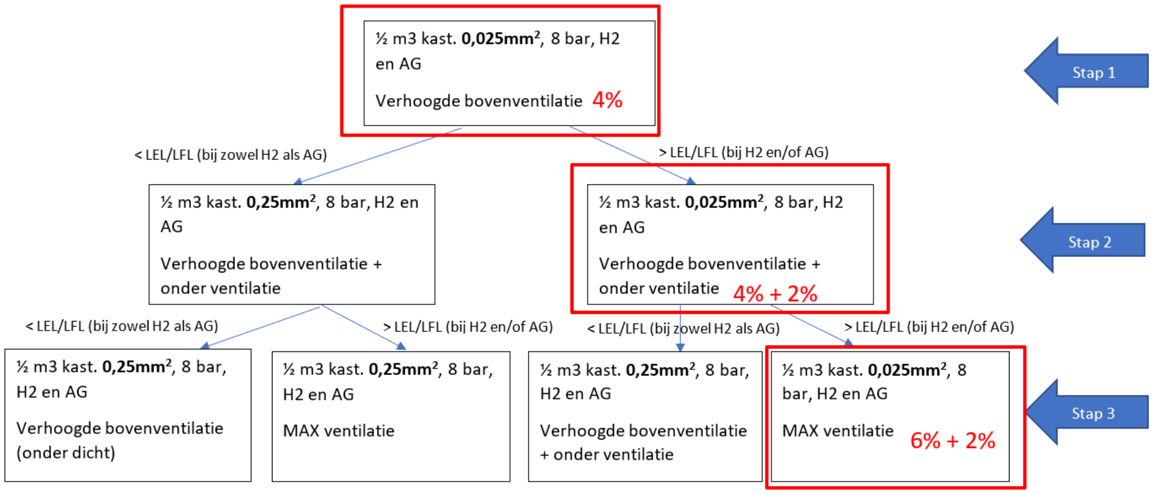


Figure 31. Steps in the dynamic test matrix.

The chosen route already reveals some details regarding the results of the experiments carried out. It is noticeable here that the route for improving ventilation is followed rather than increasing the chosen leakage opening. This indirectly suggests that improving ventilation is insufficient to adequately reduce the measured gas concentration in the casing (for both natural gas and hydrogen).

Step 1; increased top ventilation (4%) at a leak opening of 0.025 mm² and 8 bar. Compared to the baseline (2% top ventilation only), the criterion was set that the average measured concentrations of natural gas and hydrogen would be below the LEL/LFL.

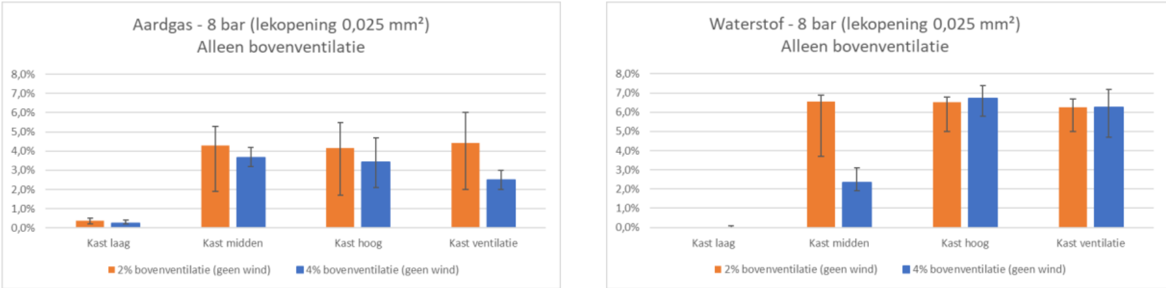


Figure 32. Increasing top ventilation from 2% to 4% at ½ m³ cabinet

When the 1/2m³ gas cabinet in unmodified form (with only 2% top ventilation) is compared with the same gas cabinet and improved top ventilation, it is noticeable that gas concentrations for natural gas decrease slightly across the board. Here, increasing the top ventilation has a positive effect on the gas concentration in the gas cabinet. The average measured values are below the LEL/LFL, while the highest measured values are above the LEL/LFL.

For hydrogen, it is noticeable that the concentration decreases in the middle of the cabinet (cabinet center) but remains almost the same high up with improved top ventilation. The average measured values and the highest measured values are above the LEL/LFL.

The error bars were used to provide insight into the dispersion of the measurements, with these bars in the bar chart representing the average measurement value.

Step 2; bottom ventilation (2%) and increased top ventilation (4%) at a leakage opening of 0.025 mm² and 8 bar. Compared to the baseline (2% top ventilation only), the criterion was set that the average measured concentrations of natural gas and hydrogen would be below the LEL/LFL. If this is not the case, a move is made to further increase the top ventilation.

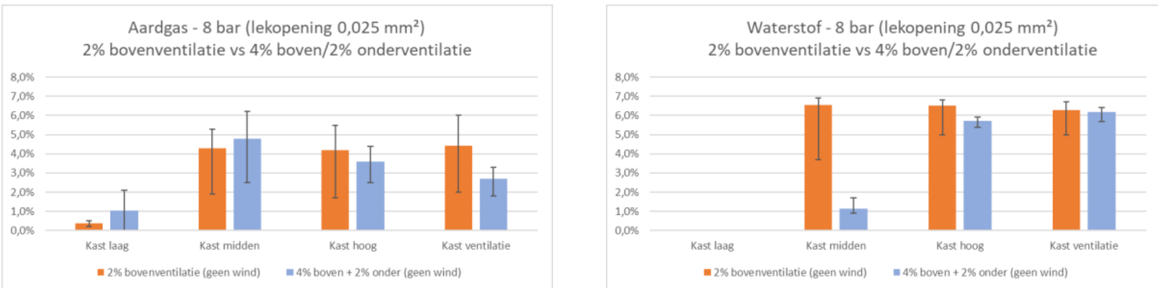


Figure 33. Increasing top ventilation from 2% to 4% and applying cross ventilation at ½ m³ cabinet

When the 1/2m³ gas cabinet in unmodified form (with only 2% top ventilation) is compared with the same gas cabinet and improved top and bottom ventilation, it is noticeable that gas concentrations for natural gas decrease slightly across the board. Here, further increasing the top ventilation has an effect on the gas concentration in the gas cabinet, however, the situation compared to step 1 is not significant.

For hydrogen, it is noticeable that the concentration decreases significantly in the middle of the gas cabinet but remains almost the same high up in the gas cabinet with improved top and bottom ventilation. A blanket of uniform hydrogen concentration forms in the gas cabinet that is not ventilated away. Both the average measured values and the highest measured values are above the LEL/LFL.

Step 3; bottom ventilation (2%) and increased top ventilation (6%) at a leakage opening of 0.025 mm² and 8 bar. Compared to the baseline (2% top ventilation only), the criterion was set that the average measured concentrations of natural gas and hydrogen should be below the LEL/LFL.

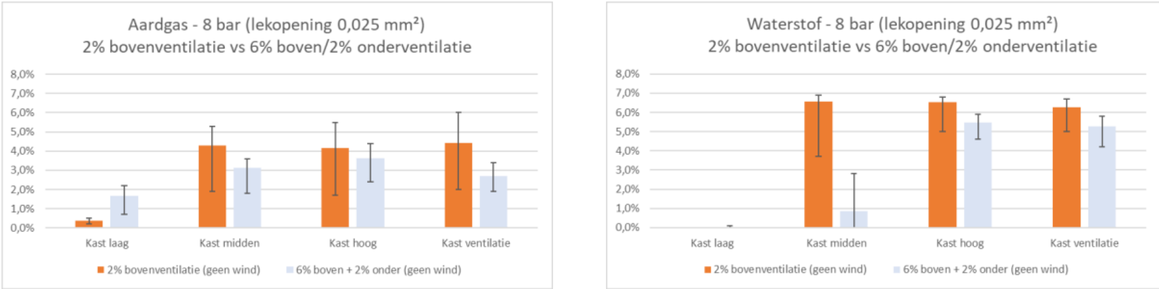


Figure 34. Increasing top ventilation from 2% to 6% and applying cross ventilation at ½ m³ cabinet

When the 1/2m³ gas cabinet in unmodified form (with only 2% top ventilation) is compared with the same gas cabinet and improved top and bottom ventilation, it is noticeable that gas concentrations for natural gas decrease slightly across the board. Here, further increasing the top ventilation has little effect on the gas concentration in the gas cabinet.

For hydrogen, it is noticeable that the concentration decreases sharply in the middle of the gas cabinet but remains almost the same high up in the gas cabinet with improved top and bottom ventilation. Again, a blanket of uniform hydrogen concentration forms in the gas cabinet that is not ventilated away. Both the average measured values and the highest measured values are just above the LEL/LFL.

In order to make a clear comparison, all measurements are included in one bar chart for natural gas and one for hydrogen. Here, for natural gas, the improvement is striking when adding top ventilation, while for hydrogen the shift in gas concentration (from mid to high in the housing) is particularly striking.

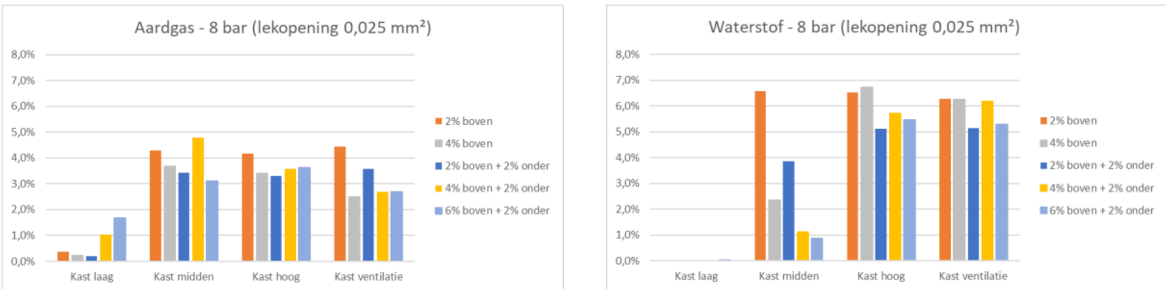


Figure 35. The effects of adjusting ventilation at a ½ m³ cabinet

In summary, <u>for this particular gas cabinet,</u> based on the above steps, it can be concluded that;

- Increasing upper ventilation leads to reductions in measured natural gas concentrations;
- Increasing upper ventilation leads to displacement of measured hydrogen concentrations. Hereby, a blanket of uniform concentration is formed that cannot be adequately ventilated away (only high concentration left at "cabinet high" and "cabinet ventilation");
- Adding underventilation seems to have a positive effect mainly for the measured hydrogen concentrations. The thickness of the "blanket" of uniform concentration decreases.

6.4 Consideration and summary results adjustments additional ventilation

Section 5.3 summarizes all results from the test matrix for the ½ m³ gas cabinet, the 4 m³ gas cabinet station and the HAS gas cabinet. All reported values are the maximum measured concentrations of natural gas or hydrogen in and around the gas cabinet. These concentrations were taken from the measurements that had a duration of 30 minutes unless the measured concentration led to an increased risk with respect to flammability limits. In those specific cases, the measurement was shorter and this is mentioned in the description of the measurement in the annex. The measurement was also stopped when the measured concentration stopped increasing significantly.

Measurements on the ½ m³ casing show a gas concentration around the lower flammability limit at a leakage opening of 0.025 mm² (at 8 bar). This applies to both natural gas and hydrogen.

Using this specific experiment, a comparison was also made between the method from the NPR and the measurements. Here, the possibility of ventilation (geometry specific) was compared with the experiments (see appendix IV). The calculation using the NPR shows whether, depending on the effective wind speed entering the geometry, it is sufficient to reduce the concentration inside the gas cabinet to 25% LEL/LFL or 10% LEL/LFL, respectively.

By assuming an effective wind speed of 0.1 m/s (windless) as the entering wind speed, it can be concluded from this analysis that the calculation according to the NPR agrees reasonably well with the results from the experiments for hydrogen at a leakage opening of 0.025 mm². In the case of natural gas at the same leakage opening, the NPR judges more positively compared to the experiments. When setting up the casing in a normal outdoor situation (not windless), no measurement results are available, however, an NPR calculation can be done. When it is assumed that the effective wind speed is 0.5 m/s, the NPR's assessment for ventilation is positive with the exception of hydrogen leakage at 8 bar.

What should also be noted is the comparison between the NPR method and the corresponding experiment at 40l/h natural gas. In a windless situation, the measured gas concentration in the casing is less than 25% LEL/LFL, which is confirmed by the NPR calculation. For the experiment with hydrogen, the measured gas concentration in the gas cabinet is greater than 25% LEL/LFL, where the NPR calculation just does come out positive and shows that the gas cabinet would comply.

For larger leakage openings (and leakage flow rates), the experiments and the NPR agree reasonably well. Here, both the NPR method and the experiments show that ventilation behavior cannot prevent the gas concentration from rising above 25% LEL/LFL.

In sections 6.2 and 6.3, the role of ventilation was further investigated by performing measurements with the ½ m³ cabinet. To minimize the role of external factors here, we chose to report the bar graphs with mean values. These values are a representation of the instantaneous measurements over time spans between 4 minutes and 30 minutes (unless situation was considered potentially risky, in which case the time span of the measurement was shortened). Error bars were then used in the bar charts to provide insight into the minimum and maximum measured concentration. For each measurement point, the length of the error bar indicates the range of measured concentrations during the experiment. This spread allows the reader to see the effect of external influences (such as wind/ natural draught). In this way, measurements can be compared at a glance.

Based on an exploratory step, it was understood that adding additional ventilation could lead to an improvement. By comparing different scenarios, a lower concentration was measured inside the gas cabinet. This step was used as a prelude to a systematic approach to analysis to improve ventilation using a dynamic test matrix.

By increasing ventilation capacity through the addition of top and/or bottom ventilation, it has been demonstrated that improved ventilation is possible. Less accumulation of gas takes place in the casing. However, it should be noted that some measured values exceed the lower flammability limit for larger leaks.

Based on the observations, the geometry of the roof seems to influence the efficiency of ventilation of this 1/2m³ cabinet. This has been previously observed during HyDelta 1.0 for the 4m³ cabinet station where the concentration at the vent openings is temporarily equal or even higher than the measurements inside the cabinet. By adding the measurement point "top cabinet" above the exit of the ventilation (in the roof point), it was made clear during HyDelta 2.0 on the basis of measurements that, especially at the larger leakage flow rates, the measured gas concentration in the roof point can become higher than the measured concentration at the vent openings. This indicates that accumulation of gas in the roof tip may occur. Due to the chosen roof geometry (for the purpose of rainwater drainage), these gas cabinets have a hydraulic resistance that needs to be overcome by the escaping gas. Due to the low density of hydrogen, more driving force is required, leading to a thicker blanket of uniform gas concentration. Here, the density difference between air and natural gas or air and hydrogen also plays an important role.

For the design of a gas cabinet suitable for hydrogen (H2 ready design), design considerations include the following:

1. The percentage of ventilation relative to floor area should depend on the gas cabinet content. This point needs further investigation.
2. Increasing the ventilation area should be further investigated with the findings from this report and current standards as a starting point.
3. Applying cross ventilation seems to contribute to an improved possibility of ventilation compared to top ventilation alone. The practical positioning of lower ventilation (in relation to plant growth and snow) should be considered here.
4. The vent openings should be placed at some distance from the top of the cabinet. Also, in literature [3] states that the quality of ventilation is maximized when the vent openings are placed 5-10% of the gas cabinet height below the roof. If the vent openings are placed too high, the crosswind sweeps too much over the gas mixture in the cabinet and the area of the vent openings needs to be multiplied by a factor of 2 or 3 to get the same effect. This effect needs further investigation.
5. Oversized roofs with the aim of preventing waterlogging should be investigated with regard to hydraulic resistance and ventilation. Such construction seems to limit ventilation capacity.

For such a step, experiments can be used as a starting point, where CFD calculations can be used to better understand the behavior of gas during a leakage.

7. Modelling flow phenomena during leakages in gas stations

7.1 Introduction

Hydrogen gas is a gas that can pose serious risks if released into an enclosed space. The potential hazards associated with the release of hydrogen gas in confined spaces include fire and explosion. It is important to understand the behavior of hydrogen gas in confined spaces to develop effective strategies for reducing risks and ensuring the safety of people and equipment.

The aim of the modelling activities is to understand what factors influence hydrogen flow phenomena in gas stations, in terms of the concentration and distribution of hydrogen gas in the gas station cabinets. This knowledge can be used to design and operate the gas stations in a way that minimizes the risks of hydrogen-related incidents and to evaluate the effectiveness of different risk reduction strategies.

Modelling can be carried out to study the effect of gas cabinets of different sizes and shapes. Factors such as the properties of the hydrogen gas, the ventilation rate, the presence of obstacles or mixing in the gas station and the initial concentration and distribution of the gas can be taken into account.

The steps and factors that ultimately determine hydrogen concentration profiles at a gas station are as follows.

1. Leakage rate: the amount of hydrogen or natural gas escaping from the pipeline through a leakage opening (in the faulty component). At sufficiently high operating pressures, which is the case on the flow inlet side of the gas station (~8 barg), explosive mixtures can be detected. For a given gas, the only parameters that determine the leakage rate are the pressure and temperature in the pipe, the leakage opening and a *discharge coefficient* that provides correction of the effective permeability.
2. Diffusion: the rate at which hydrogen or natural gas diffuses into the gas station is determined by several physical processes. The first mechanism is convection, due to the head movement of the gas through the release jet and the buoyancy (density differences) between the released gas and the air in the gas station. Secondly, diffusion drives molecules from an area of high concentration to an area of low concentration due to random molecular movement. A third mechanism is ventilation, which can be natural through openings or forced in case of using a mechanical device. In a gas station, only natural ventilation is used. These mechanisms are shown in Figure 36.

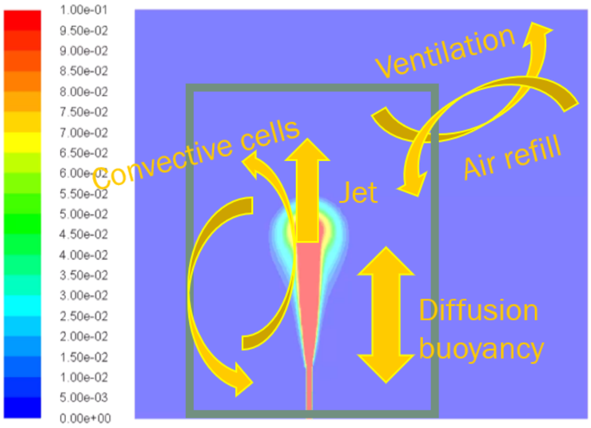


Figure 36. Mechanisms driving the transport of a gas pollutant (in this case hydrogen) within the gas station (green box) after a leakage has occurred. Ventilation slits are available at the top of the cabinet.

7.2 Literature review

The literature review has focused on the techniques used in simulating the dispersion of gases in confined spaces. Publications typically focus on scenarios that take place in domestic, mobility or industrial environments. As mentioned in the previous section, the problem of a hydrogen leak in a gas station can be more generally described as that of an unvented gas release in an enclosed space with passive ventilation. As the use of CFD simulations for hydrogen accident investigation is currently receiving a lot of attention, the literature review summarised in this report is limited to publications whose research area is very similar to the research area of this report.

Ref. [15] presents a blind CFD benchmark of hydrogen emission and flow phenomena in an enclosed space with passive ventilation. However, this is not the first reference that attempts to benchmark CFD for hydrogen accumulation in confined spaces: the article recalls two other similar CFD benchmarks performed with similar objectives but for much larger confined spaces. The volume used in ref. [15] considered is of the same order of magnitude (~1 m³) as that of the gas station selected for CFD simulations (0.5 m³). In the experiments, helium was used instead of hydrogen due to safety reasons and properties of the gas. The experiments also included the effect of wind conditions [16] investigated, although the simulations were carried out under windless conditions. Different apertures were used. Three different parties were invited to perform CFD simulations to determine the concentrations of the pollutant (helium) at different positions in the confined space. Each party used a different CFD solver and turbulence model. All parties developed a model in which the outside environment was represented by a sufficiently large volume. If the chosen volume was too small, there would be inaccuracies in the calculated flow profile around the vent opening. In all cases, buoyancy was implicitly captured by calculating for the mass ratio of helium over the whole model. The main differences between the CFD approaches were the turbulence model (URANS, LES), the numerical discretisation methods and the use of boundary conditions. In general, all CFD formulations produced satisfactory results for all openings considered. However, it was found that numerical methods, especially based on URANS, largely overestimated the pollutant concentration at the bottom of the confined space, hypothetically due to artificial overestimation of turbulent diffusion. The benchmark concluded that CFD represents a suitable approach to investigate ventilation characteristics of enclosed spaces similar to the space used in the validation experiments and with similar opening principles

The results of the benchmark efforts were later incorporated by the same authors into a best practice guideline and a broader assessment of how to perform CFD simulations for hydrogen flow problems in confined spaces [17] [18].

More recently, Lee et al. [19] conducted CFD studies for a hydrogen pressure control station similar in characteristics to the gas stations studied in HyDelta. Good agreement was found between CFD and experiments, allowing the researchers to investigate the effect of alternative ventilation. A combination of the Bousinessq hypothesis, the species transport model and the κ–ω SST turbulence formulation performed best.

Based on these references and those discussed above, the following are presented in Table 6 some recommendations for the CFD simulations that are useful for the investigation of gas stations.

Table 6. Recommendations applicable to hydrogen release within a gas station, based on the guidelines given in references [17], [18].

Subject	Recommendations
Domain	Extend the simulation beyond just the position of the ventilation to remove any edge effects of the physical air-hydrogen exchange at the ventilation.
Grid	Apply increased resolution in regions with strong gradients, such as around the hydrogen injection nozzle, jet-wall impingement point and ventilation.
Leak injection	Either as a volume source term or as a boundary source characterised by its velocity at a selected area/surface. The latter is preferred.
Gas properties	Follow a mixing approach based on mass fractionation of the different species and volume-based for density.
Turbulence model	No clear recommendation between RANS-based or LES-based approaches. RANS preferred because of lower cost, but with additional bouyancy terms.
Preconditions	If the domain advice is followed, fixed pressure limits, zero gradient or even symmetry limits are possible.
Time step	It is generally assumed that the size of the time step should be small, with CFL (Courant number) values around 10 (5-20) in case of κ–ε turbulence modelling. For LES, this is lower than 1.
Numerical diagram	There are no specific recommendations, but all benchmark studies used at least second-order schemes for the convective terms.

7.3 Modelling approach

Different modelling methods can be used to predict the concentration profiles of hydrogen in a (ventilated) space. The purpose of modelling is to provide a better understanding of the experimental results. Two levels of modelling are pursued. The first level is based on a combination of empirically validated models included in the HyRAM+ toolkit, which provides almost instantaneous results. The second level is based on CFD, which can take a long time to provide answers for a given case.

Basis and set-up of the HyRAM+ calculations

HyRAM+ [20] was chosen to provide an initial prediction and perspective on what concentration levels can be achieved in the event of a hydrogen or natural gas leak at a gas station. The results of HyRAM+ can be compared with the experiments and with the CFD modelling results.

The modelling approach used in the HyRAM+ tool follows ref. [2]. The basis of the model is a mass balance within an assumed homogeneous layer created at the top of the space when hydrogen is released. The release is modelled with a jet model. The plume formed carries hydrogen into the layer.

Ventilation reduces the accumulation of hydrogen in the assumed layer. Ventilation can be naturally driven by buoyancy, standard at the top, but can also be additionally supported by wind or a mechanical fan.

For the calculations performed with HyRAM+, the following assumptions or boundary conditions are used:

- Hydrogen is released from a tank at a pressure of 8 barg, representing the upstream side of a gas station.
- The leak diameter is selected so that the hydrogen leakage rate matches the experimental values. The leak is located at the centre and 30 cm above the ground, and facing upwards.
- Ventilation: ceiling ventilation only without the presence of wind or mechanical support. The area of ceiling ventilation is based on a 15 mm gap extending over 3 of the 4 sides of the gas station housing cover (the two long sides and one short side - the other short side has a plate that largely blocks the ventilation flow).
- The temperature of both the released hydrogen and the environment is assumed to be equal at 15 degrees Celsius.

Boundary conditions and setting for CFD simulations

The modelling setup first had to be verified against a selection of experiments conducted in the former HyDelta 1 phase (reported in [2]) and the current HyDelta 2 phase. Since the HyDelta 1 data were already available at the beginning of HyDelta 2, this set was selected first for validation purposes. The HyDelta 1 experiments took into account a number of independent conditions when investigating gas station ventilation:

- Gas station cabinet design: a 1/2 m^3 or a 4 m^3 station.
- The gas used for the leak: natural gas (G-gas) or hydrogen.
- Wind protection or not
- The actual buoyancy/nozzle diameter that ultimately determines the leakage rate.

An overview of the experimental matrix of HyDelta 1 is shown in Figure 37. Due to the cost per CFD calculation, only a subset was selected for validation of the CFD simulations. The 1/2 m^3 case was selected because higher concentration levels were found in the experiments. The cases with wind protection by a tent were also interesting but not selected because this is a difficult boundary condition for the CFD from a dynamic point of view (average wind speed variations and wind gusts). Also, a no-wind condition is also a more conservative scenario because wind will improve ventilation. In general, this means that the 1/2 m^3 cabinet is simulated for leaks of G-gas and H_2 without considering wind

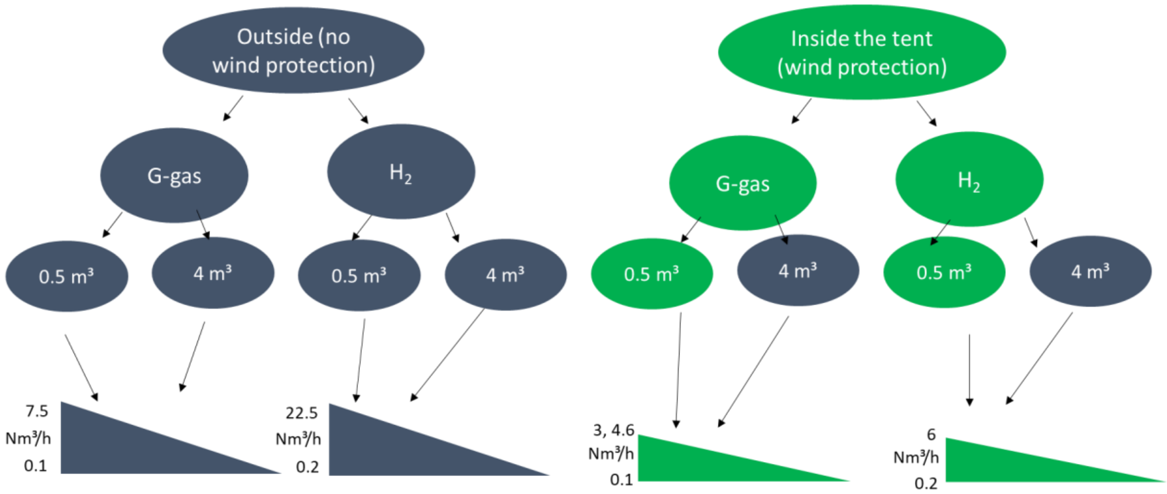


Figure 37. Overview of experiments performed in HyDelta 1.0 [21]. The path highlighted in green indicates the cases selected for CFD validation.

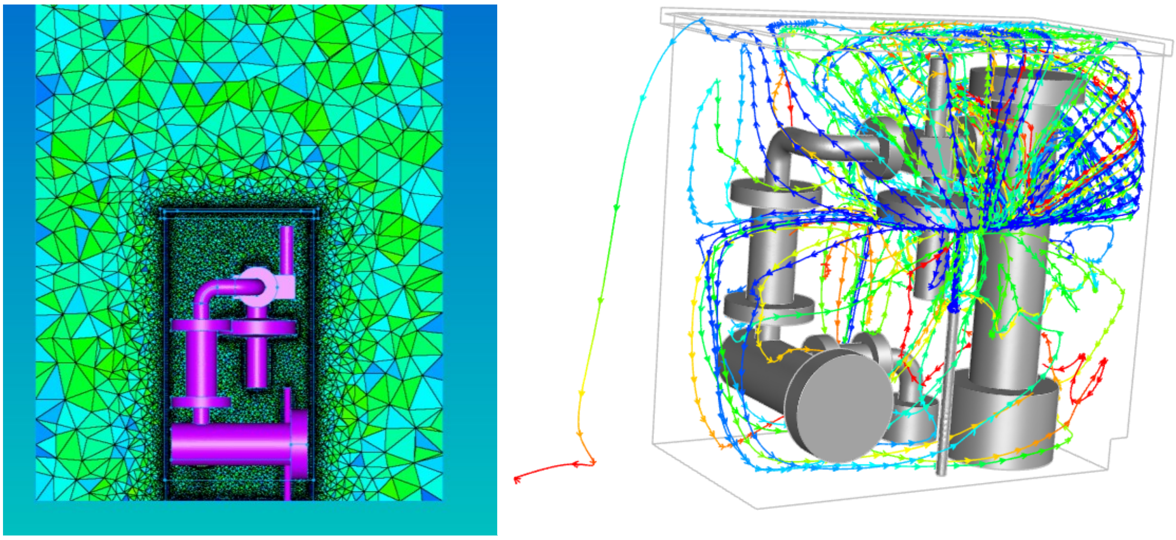


Figure 38. The initial model setup showed the gas station with equipment (left) and limited coverage of the model for the outdoor environment. Enhanced mixing was found to occur as a result of the jet "colliding" with a flange (right), which could not be validated from the experiments. The final model setup is shown in Figure 39.

The simulations were performed on the ½ m³ cabinet. Some simplifications were applied to the cabinet geometry to make the model ready for grid generation. Equipment in the gas station (e.g. pipework, valves, etc.) was finally not modelled (Figure 39), as this reduced the grid quality and increased the mixing speed as the jet stream collides with the flange (Figure 38). A 4 m × 3 m × 3 m domain was built around the cabinet to model the environment of the gas station. This final size of the outer domain is the result of early attempts with a smaller domain (1.5 m × 2 m × 2 m), which combined with pressure outlet boundary condition brought unphysical side effects to the area of interest. The creation of the computational grid was performed in Pointwise resulting in hybrid computational grids that contained mainly tetrahedral cells and some hexahedral cells. After importing the computational grid into ANSYS Fluent, the tetrahedral cells were transformed into polyhedral cells to reduce the number of cells and improve grid quality. An example of the grid is shown in Figure 39. Local grating refinement was applied at the leakage opening and at the walls of the case, on both sides. The total number of cells is about 3.7 million.

The model was set up according to ref. [15], i.e. using RANS turbulence modelling with the realizable k-ε turbulence model and extended wall function description. Full description of upwelling effects were included which means that upwelling forces affect turbulence production and breakdown. Specimen transport was modelled using a grouped specimen for "air" and another for hydrogen. The energy equation was not solved. The density at each point where a mixture of air and hydrogen is present was calculated using the volume-weighted average. The properties of the individual species were held constant and can be found in Table 7. Although the viscosity of hydrogen is of the same order of magnitude as that of air, its density is an order of magnitude smaller. This means that hydrogen moves strongly upwards when released into the housing.

With respect to boundary conditions, all surfaces representing the ground or bottom of the cabinet were modelled as walls. Also, the four side surfaces of the volume representing the outside environment were modelled as walls. The top surface was modelled with a constant pressure boundary condition. The leakage was modelled as an inflow with an area of 2 mm^2 , which is significantly larger than the actual orifice used in none of the experiments. This was done to avoid very small grid distances that would significantly increase the computation time. However, the mass flow was maintained at the target value for comparison with the experiments. This affects the environment close to opening, but not the overall distribution of hydrogen in the cabinet. This actually corresponds to placing the "virtual" inflow at a point where the jet is already plotted.

The main results sought in the CFD simulations are the concentrations of hydrogen in air. The virtual measurement points are points P1-P2-P3-P4, which correspond to measurement locations 1-2-3-4 (Figure 17).

Table 7. Properties of the gases used in the CFD simulations.

Feature	gases		
	Air	Hydrogen	Natural gas
Density [kg/m]³	1.225	0.082	0.833
Viscosity [μΠα s]	17. 9	8.4	11.4

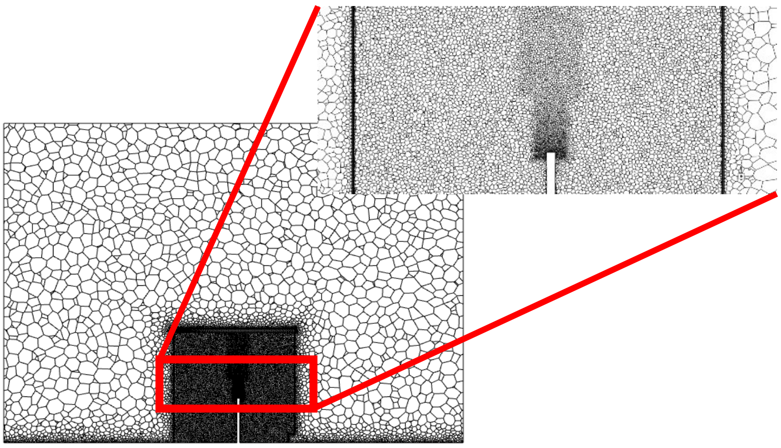
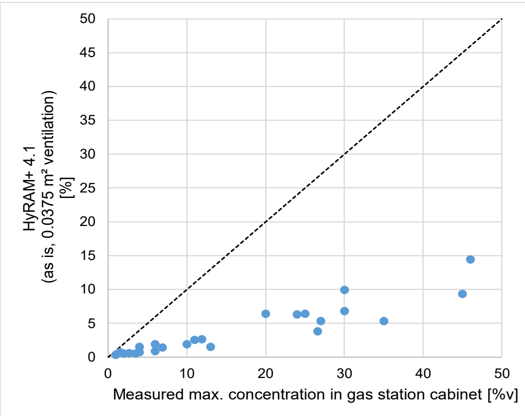


Figure 39. Polyhedral computational grid used in the CFD simulations and local grid refinement around the injection nozzle (top right).

7.4 Results of simulations with HyRAM+

Simulations with the HyRAM+ tool were calculated for all experimental cases performed during HyDelta 1.0 [2] and the 1/2 m³ case of HyDelta 2.0 (as presented in this report), including those for hydrogen and natural gas. Under the assumptions described in section 7.3, the model consistently predicts concentrations about a factor of 3 lower than those measured during the experiments. This is shown in Figure 40. The main reason for this is probably that the geometry of the vent area does not match the archetype assumed in the HyRAM+ model, as hydrogen has to follow a winding path to exit. This path even includes a downward segment (against the upward force of buoyancy) that can only be traversed by floating overpressure. In the HyRAM+ model, the ventilation area is in the same plane as the vertical wall of the gas cabinet, which separates the inside of the gas cabinet from the outside environment. To match the measured concentrations, a much smaller ventilation area would have to be introduced, which is about 10 times smaller than the geometrically selected value. Alternatively, the outflow coefficient should be adjusted, although the effect is equivalent. The value fluctuates, with cases exposed to wind requiring a smaller area correction than those where the tent was present. This is reasonable, as wind provides additional ventilation, which can be translated into an effectively larger ventilation window. Wind effects can potentially be captured in HyRAM+, but only through from user input, and not as a result of the physical model itself.

Overall, the main conclusion is that the geometry of the ventilation slits of a typical Dutch gas station cabinet makes the use of modern, standard models such as those in HyRAM+ difficult to apply. A correction factor on the ventilation area of about 10 would give reasonable results compared to the experiments performed in this program.



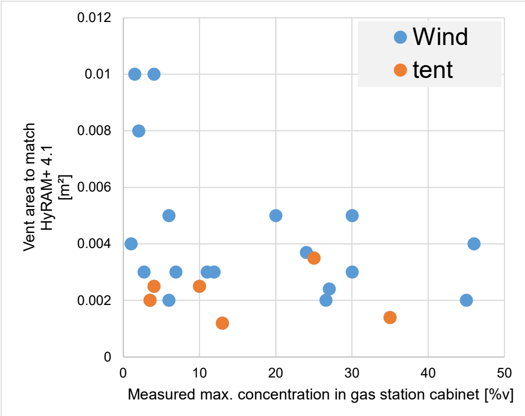


Figure 40. Left: comparison of the results of HyRAM+ with those of the experiments performed in HyDelta 1.0 and HyDelta 2.0. If all points in this graph coincided with the dotted line, it would mean that there is perfect agreement between the model results and the experimental results. The model underestimates the measured concentrations in the cabinet. Right: area of ventilation to be introduced in HyRAM+ model to match measured concentrations, distinguishing between cases where the cabinet is exposed to (varying strength of) wind and cases where it is protected by a tent.

7.5 Results of the CFD simulations

Many simulations were done to study the sensitivity of modelling options until a final setting was determined (as described in section 7.3). Here, only the most relevant simulation results are described with respect to the measurement campaigns in HyDelta 1.0 [2] and Hydelta 2.0. The overview of the simulations performed is given in Table 8, which forms the basis of the following subsections. When the results are compared with experiments, only the cases in the windless situation (inside the tent) are considered.

Table 8. Summary of simulations performed with the described setup.

Simulation ID	Leaked fluid	Leakage flow rate [Nm³/h]	Comments
01	Hydrogen	6.0	HyDelta 1, 8 barg, 0.25 mm²
02	Hydrogen	0.6	HyDelta 2, 8 barg, 0.025 mm²
03	Hydrogen	0.6	02 with sensitivity to jet direction
04	Hydrogen	0.6	02 with sensitivity for vent opening design
05	Natural gas	3.0	HyDelta 1, maximum flow rate with tent protection
06	Natural gas	0.45	HyDelta 1, flow rate lower than 05

Simulation-01 - Hydrogen, 6 m³(n)/h

The first simulated case involved the emission of 6 m3(n)/h H_2 . This case simulates a leakage gap of 0.25 mm^2 with a pilot pressure of 8 barg from the network. This corresponds to a mass flow of 0.15 g/s which was applied in the CFD. After 8 minutes, hydrogen emission is stopped.

A contour plot of the velocity magnitude is shown in Figure 41. Here it can be seen that the jet hits the lid of the cabinet and then flows along the top to the sides of the cabinet. The momentum of the jet drives circulation down and along the walls of the cabinet. In Figure 43 contour plots of the H_2 (%v) are presented. Because of the high speed of the jet, the hydrogen mixes reasonably well in the cabinet and some H_2 also escapes through the vent openings to the outside, where it moves upwards due to the upward buoyancy force. The behavior is not so similar to the theoretical archetypes based on a homogeneous layer. This is due to the large momentum of the jet. The hydrogen concentration reaches steady state after about 6 minutes, as shown in Figure 42 where the time evolution is plotted for different locations in the cabinet. Also plotted in this figure are the measured values, where '**L**' stands for the lower location and '**H**' for the higher location.

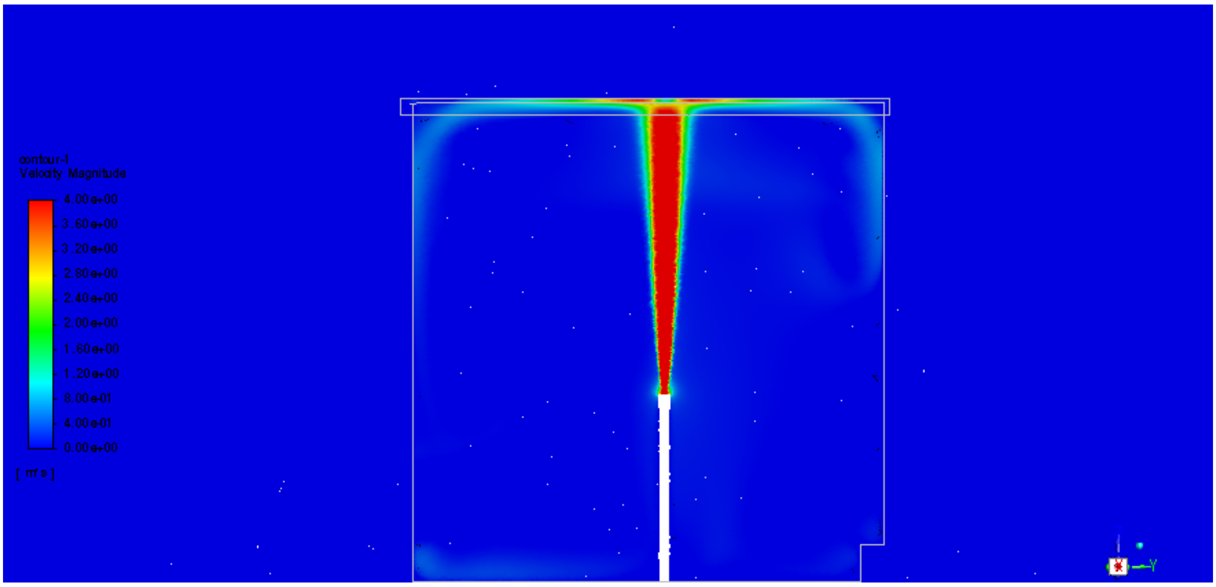


Figure 41. Contour plot of velocity magnitude in a plane through the leak.

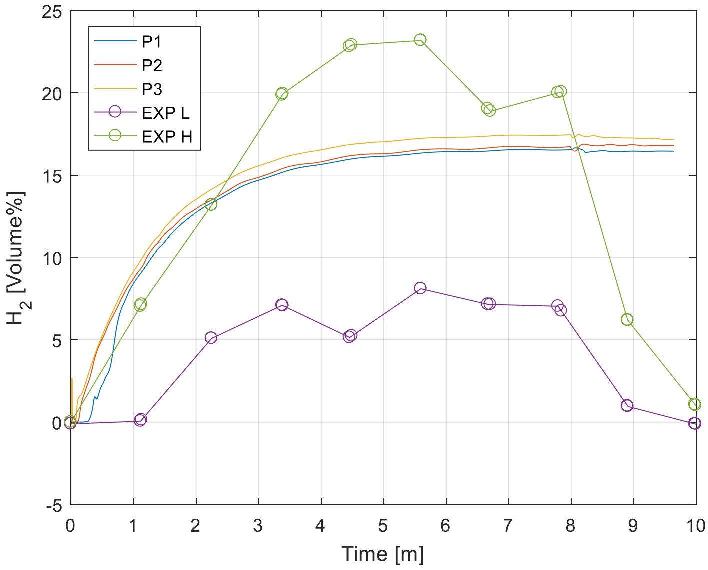


Figure 42. Concentration of H2 at three sites (P1-P2-P3) compared with the experimental measurements (EXP L and EXP H) for flow rate 6 m³ (n)/h H₂ .

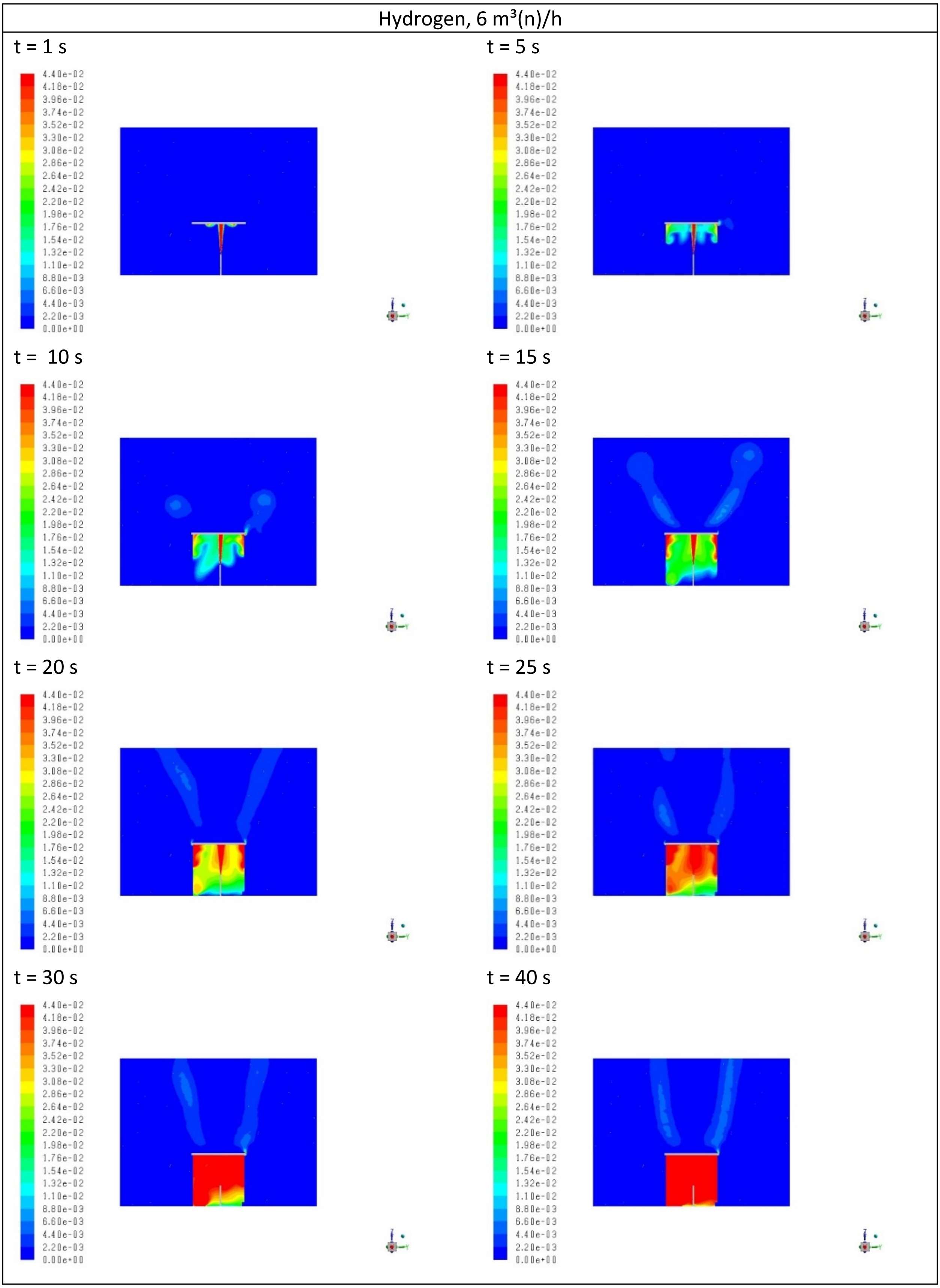


Figure 43. Contour plots of the concentration H_2 (volume%) at different times. t=1,5,10,15,20,25,30 and 40 s. The contour is truncated at 4.4%, the lower flammability limit of H_2 .

Some observations that can be made from Figure 42 are:

- The initial buildup of hydrogen at the top of the cabinet is in reasonable agreement with the experiments. The final equilibrium concentrations at the top of the case (P2, P3) are also very similar and agree with the measured values.
- The time to reach equilibrium is also fairly similar, between 5 and 6 minutes.
- For P1, the lowest point, the simulation overestimates the equilibrium concentration to the point where little or no stratification is seen within the cabinet. This means that circulation created by the jet has a dominant influence compared to upwelling, but possibly also that ventilation is insufficient. There is little competition between heavier fresh air and upward hydrogen to occupy the space near the bottom of the cabinet.
- After 8 minutes, when the leakage in the experiments stops, the concentrations do not change in the simulation, while the values in the experiment drop rapidly. This indicates that, according to the simulation, ventilation is poor and fresh air from outside is not entering the cabinet (or conversely that hydrogen is trapped in the cabinet). The transportation to the outside is insufficient for the concentration in the cabinet to drop.

Simulation-02 - Hydrogen, ~ 0.6 $m^3(n)/h$

A case from HyDelta 2.0 is then calculated for a leakage of about 0.6 m3(n)/h, corresponding to a mass flow of 0.015 g/s. This case simulates a leakage opening of 0.025 mm^2 with an inlet pressure of 8 barg. Looking at the contour plots in Figure 44 we see that the flow is less turbulent and hydrogen slowly forms a layer at the top of the case but does not flow easily through the vent opening. The behavior is very similar to theoretical frameworks that assume a homogeneous layer of growing thickness until an equilibrium between source and vent opening is reached. The behavior is also visible in Figure 45, where the concentrations at different measurement points are plotted. For comparison, the CFD data from the previous case is also given here. As expected, the build-up is slower, but does not reach a plateau as in the previous case. Also, the concentration values obtained in the simulation are much higher than those obtained in the experiments, indicating that the model captures less effective ventilation than during the experiments. In addition, the concentrations obtained are higher than those obtained at higher flow rates, indicating that without driving impulse from a jet, the cabinet is not ventilating. In the case of the higher flow rate (simulation-01), the impulse remaining in the hydrogen upon hitting the lid is sufficient to drive some of it out. At a lower flow rate, this is not the case and the cabinet is able to collect more hydrogen. After 18 minutes of simulation time, the simulation is stopped.

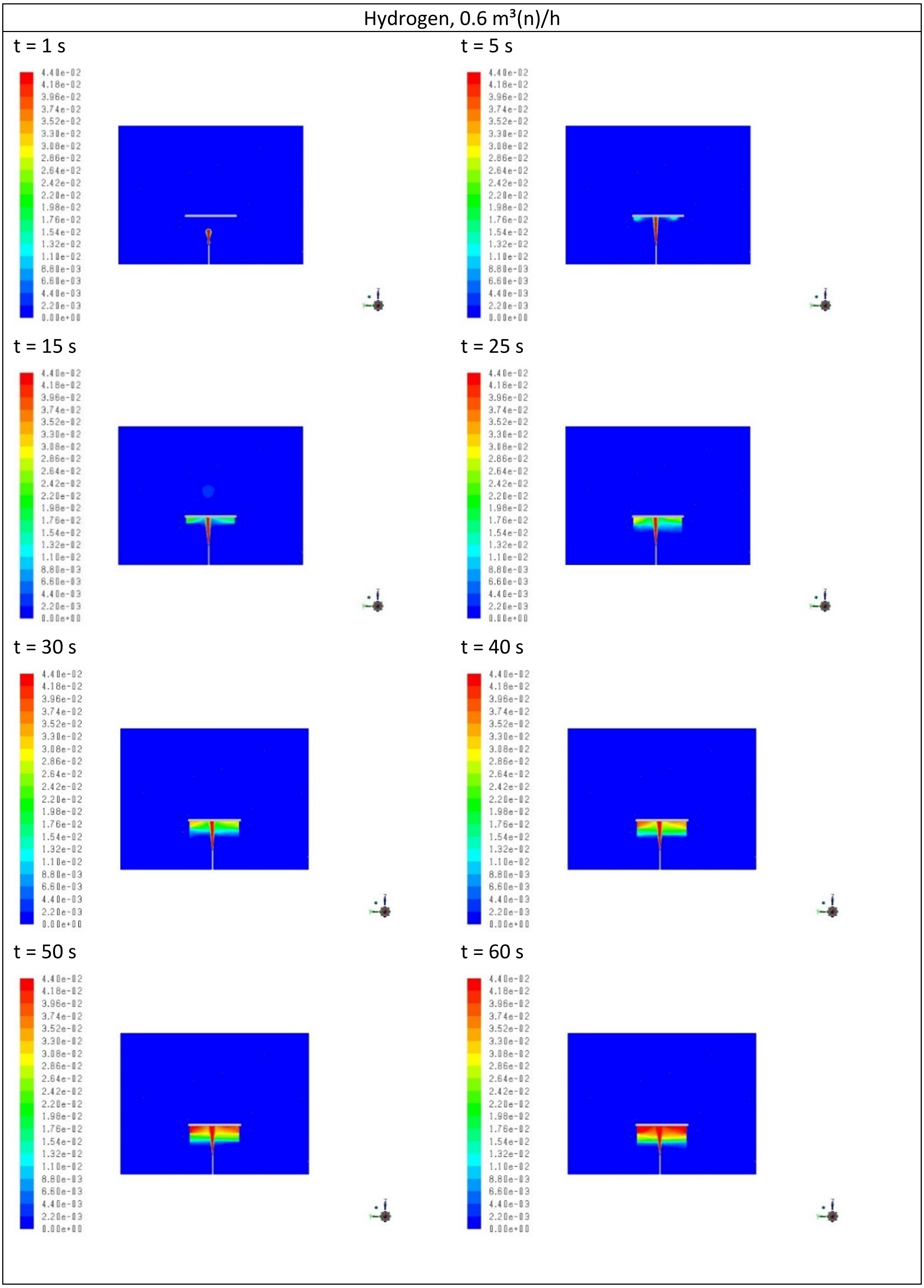


Figure 44. Contour plots of the concentration H_2 (volume%) at different times. t=1,5,15,25,30,40,50 and 60 s. The contour is truncated at 4.4%, the lower flammability limit of H_2

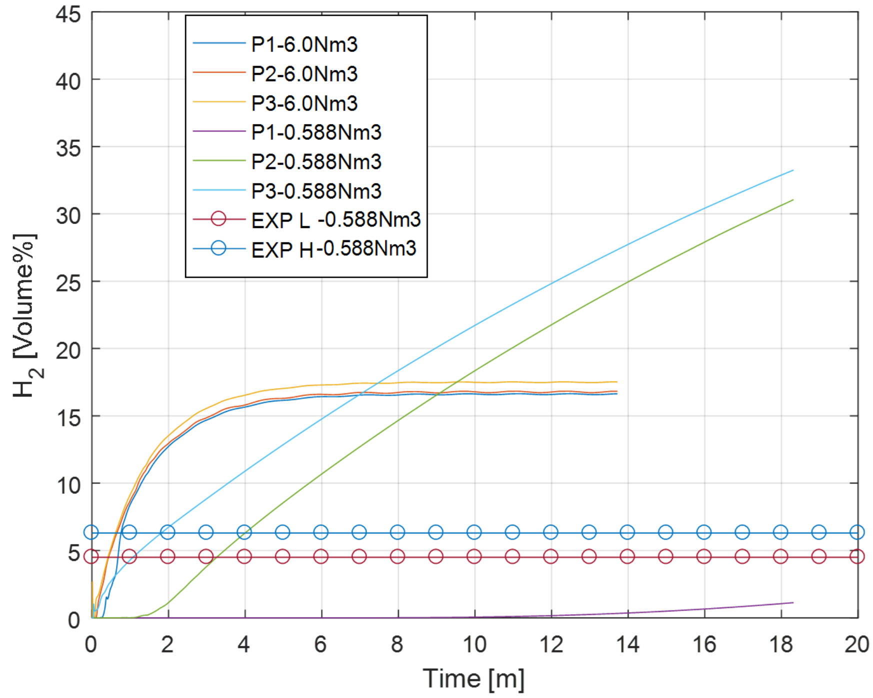


Figure 45. Concentration of H_2 at three locations compared with the experimental measurements of flow rate 0.588 m3(n)/h of H_2 . Simulation results of the 6 m3(n)/h case are also given for comparison.

Simulation-05 & Simulation-06 - natural gas, 3 m³(n)/h and 0.45 m³(n)/h

Two cases with natural gas (NG) leakage are performed. The difference is only in the leakage flow. The high flow with 3.0 Nm3/h and a lower flow of 0.45 m3(n)/h. Results can be seen in Figure 46 and Figure 47. In Figure 46 the contours of NG are plotted for both cases. The case with the high flow rate mixes much faster but, because of the momentum of the jet, NG can be strongly ejected outside the cabinet. This also draws in more fresh air. In the low leakage flow case, a build-up of natural gas is formed from the top lid of the cabinet, and the emission of natural gas to the outside is hardly visible in the contour plots. By looking at the values at the measurement points in Figure 48 it can be seen that the equilibrium concentration is almost the same for both cases. This is an unexpected result because the experiments show a higher value for the higher flow rate. However, it is consistent with the behavior also observed in the hydrogen case when comparing simulations 01 and 02, where a lower leakage current results in a higher concentration inside the cabinet.

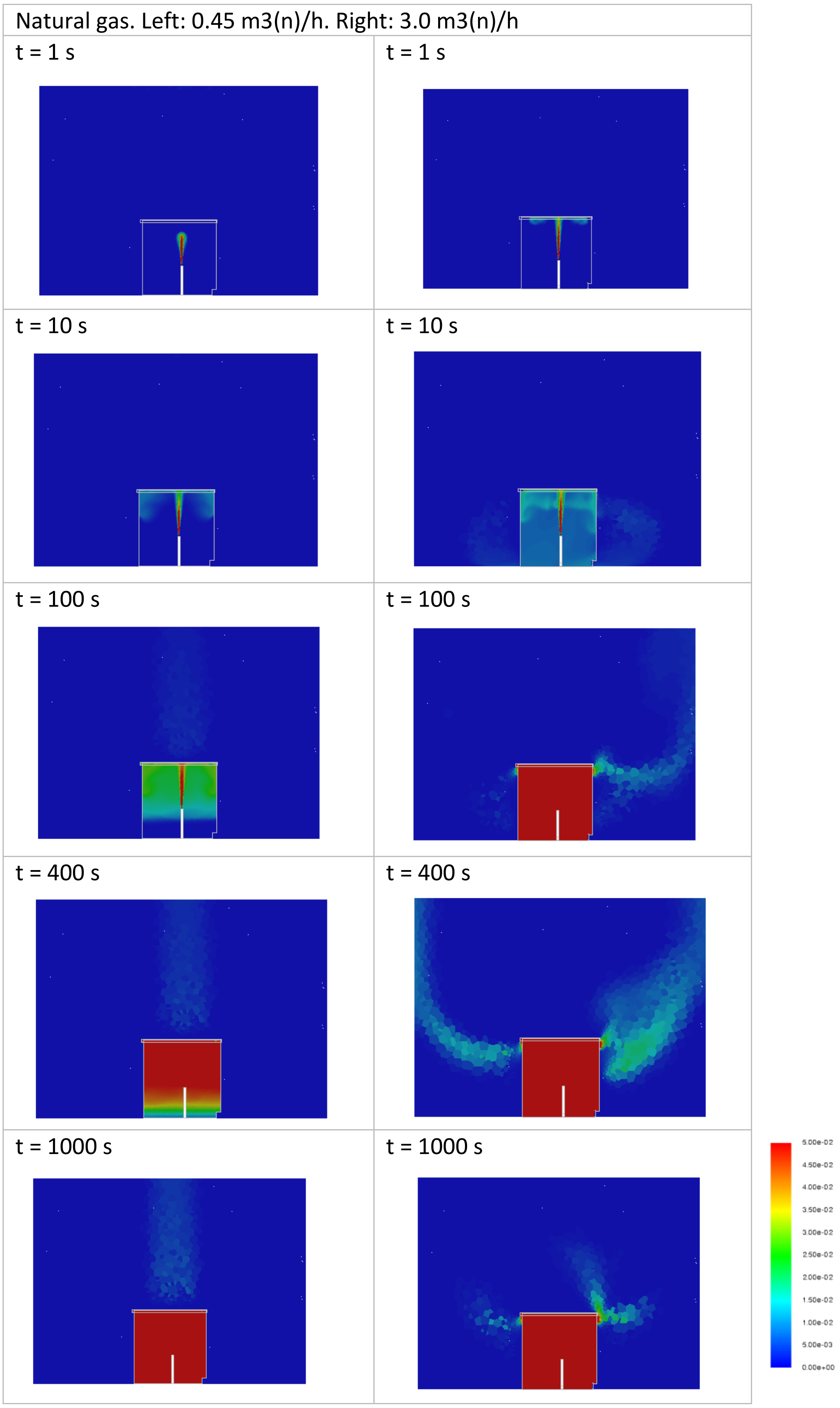


Figure 46. Contour plots of natural gas concentration for both cases. Left: 0.45 m³ (n)/h. Right: 3.0 m3(n)/h. Time values (from top to bottom) are 1.0 s, 10 s, 100 s, 400 s and 1000 s, respectively.

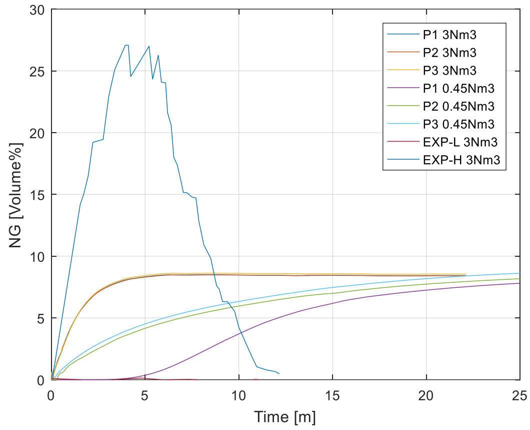
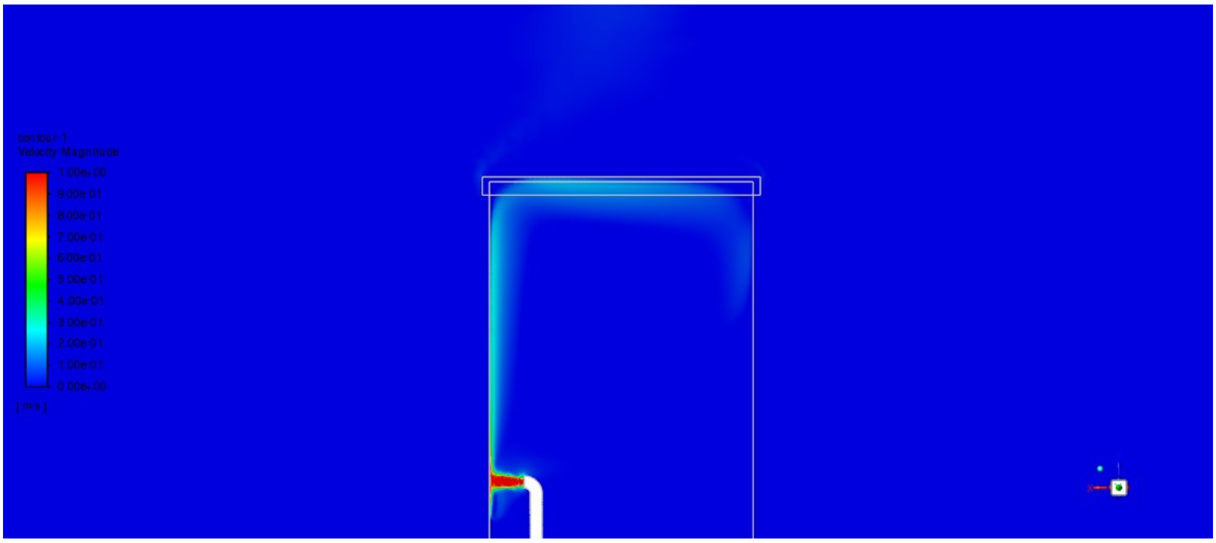


Figure 47. Concentration of NG at three locations for both the 3 m³ (n)/h and 0.45 Nm³ (n)/h natural gas outflows. Experimental results for the 3 m3(n)/h flow rate are also given for comparison.

Simulation-03 - Leakage in horizontal direction

A sensitivity scenario is simulated with a horizontal leakage of hydrogen. The flow field is depicted in Figure 48. Here it can be seen that the flow collides with the wall and flows mainly upwards. Some of it also flows downwards. Looking at the concentrations at the measurement points shown in Figure 49, there is little difference between the vertical and horizontal cases. The values of P2 and P3 are closer together for the horizontal leakage, meaning that better mixing takes place inside the cabinet in the case of horizontal leakage.



7Figure 48. Contour plot of the velocity field of simulation 03, with the leakage released in the horizontal direction. This configuration has not been used with experiments

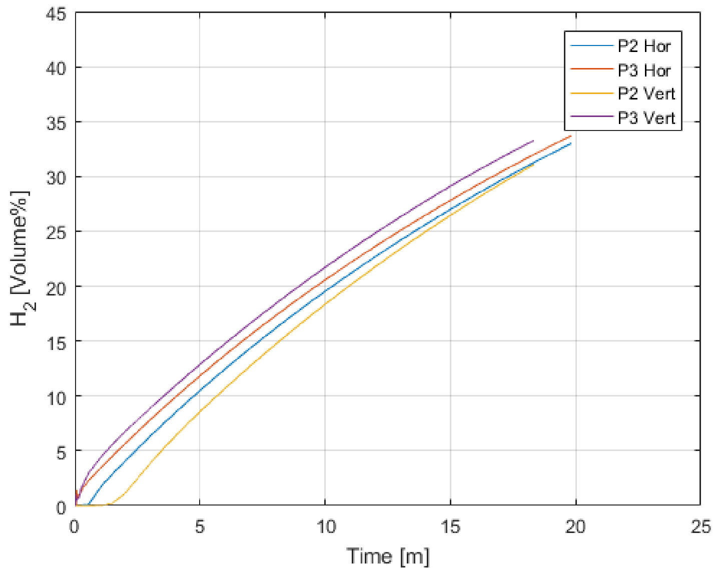


Figure 497. Concentration of H_2 at three locations for the case of horizontal leakage outflow, compared with the experimental measurements of the ~0.6 m3(n)/h outflow of H_2 .

Simulation-04 - Different ventilation design

It was discussed in previous sections that the geometry of the gas station ventilation ducts provides resistance to hydrogen outflow in case of a leak. An important barrier is the overhang of the lid. Hydrogen arriving at the top must first flow downwards (against its natural upward tendency) to leave the gas station cabinet. This can only happen if there is sufficient opposite pressure. Only when the gas flow is strong enough is there enough momentum in the flow (or stagnation pressure) to reach the bottom of the overhang and flow out. It was interesting to understand to what extent the overhang is indeed an effective barrier to hydrogen outflow. A simulation was therefore carried out in which the overhang was removed. This is shown in Figure 50. The selected leakage flow rate is ~0.6 m^3 (n)/h. Practical implications of removing the overhang, such as protection against water intrusion or malicious acts, are currently ignored.

The results of the simulation are shown in Figure 51 and Figure 52. Removing the overhang has a clear effect on reducing the concentration of hydrogen within the gas cabinet. Such a design provides better ventilation. It is therefore recommended to investigate alternative ventilation designs that allow hydrogen to follow its natural upward movement while providing sufficient protection from external factors.

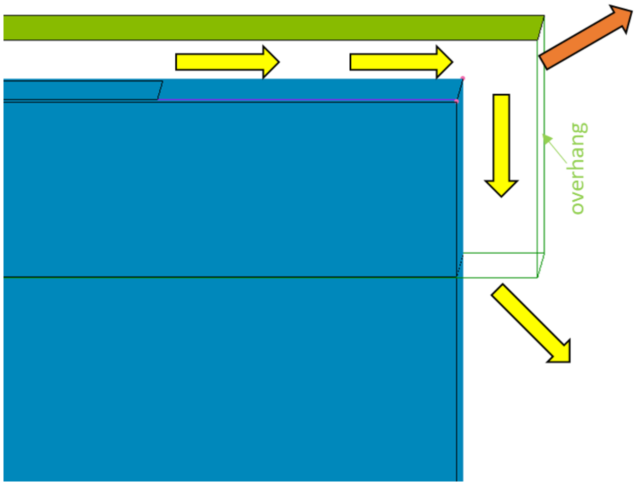
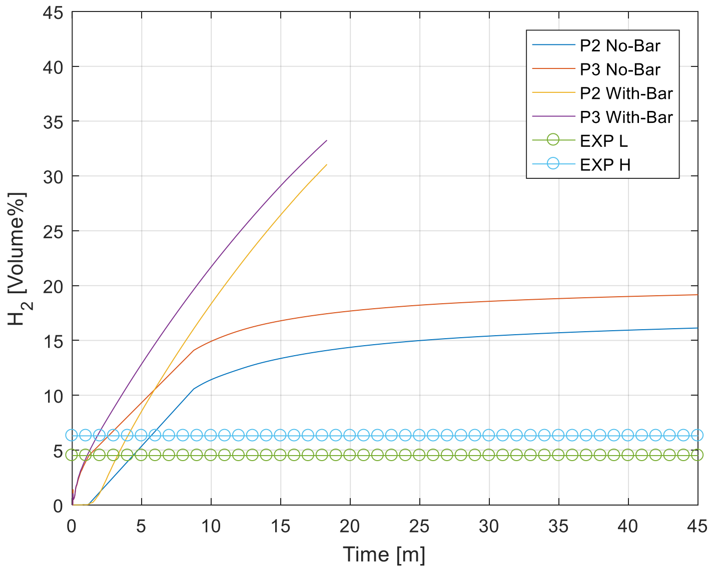
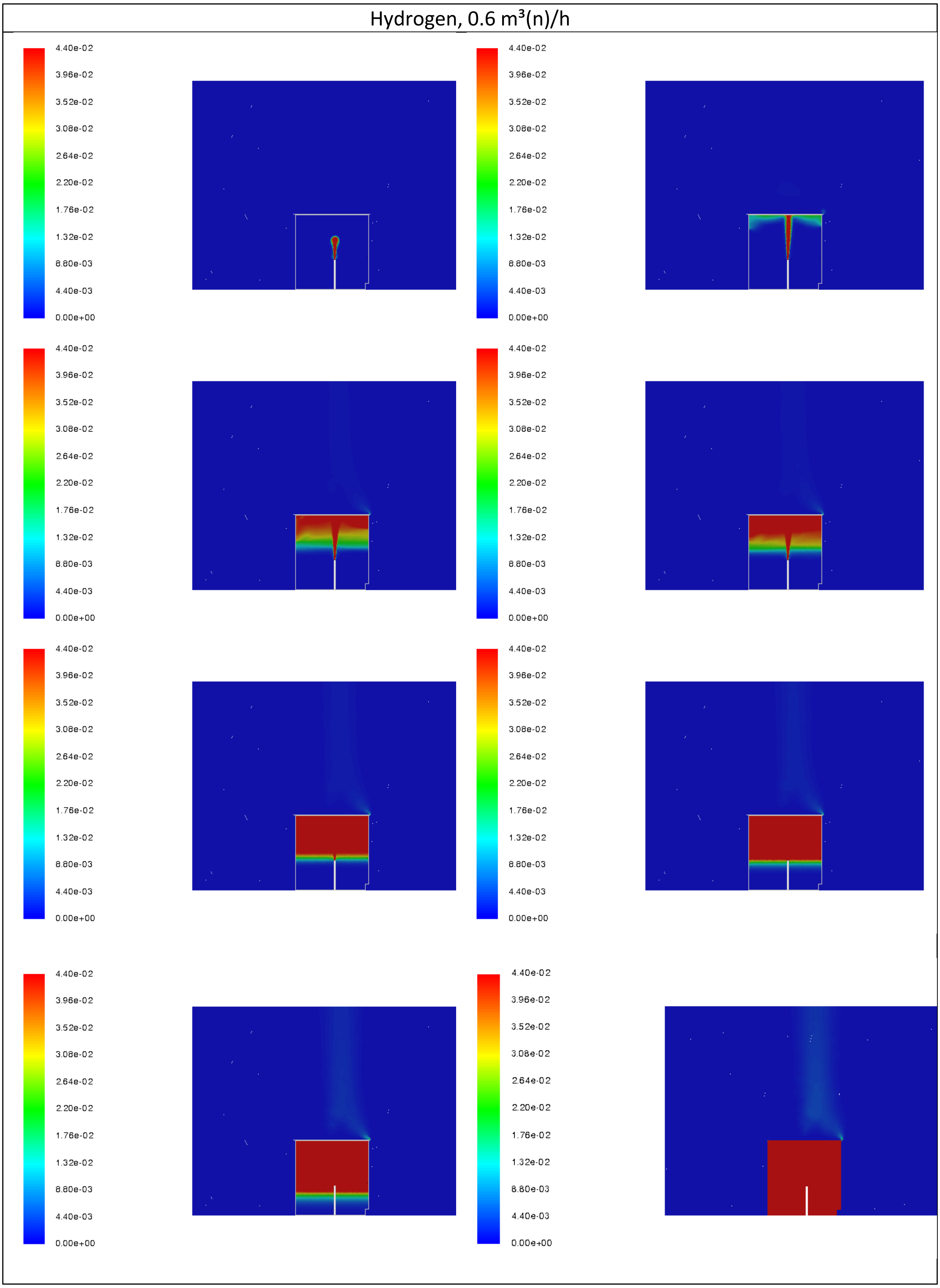


Figure 507. Detail of the missing overhang removed in simulation 04. The wall surfaces of the lid are shown in green, forcing hydrogen to follow the yellow arrows to leave the gas cabinet. In simulation 04, the lateral surfaces (overhang) are removed, allowing hydrogen to leave the gas cabinet.



7Figure 51. Concentration of H_2 at three locations for the case without overhang, compared with experimental measurements of the ~0.6 m^3 (n)/h release of H_2 . For comparison, the case with overhang is also shown (also applies to experimental results).



7Figure 52. Contour plot of the concentration of H_2 (volume%) at different times. t=1, 10, 60, 100, 200, 300, 600 and 900 s. The contour is truncated at 4.4%, the lower flammability limit of H_2 .

7.6 Conclusi es CFD

The different modelling activities were introduced to better understand the result of the measurements. To do so, good agreement between the models and experiments is a prerequisite. The following conclusions can be drawn:

- Modelling based on modern, standard engineering tools such as HyRAM+ or the CFD visualize the design of housing ventilation. Both techniques map the build-up of gas concentration for the chosen leakage rates where the same conclusions can be drawn in terms of order of magnitude.
- Modelling confirms that the gas concentrations for large leaks of hydrogen-air mixtures within the cabinet are above the LFL, as found in the experiments. Ventilation for these scenarios are limited in the current design.
- The ventilation route is important and should facilitate the upward flow of hydrogen driven by buoyancy. An alternative geometry that removes the overhang of the cabinet lid confirms a significant improvement in ventilation.
- Whether the leakage is vertical or horizontal does not strongly affect the concentrations within the cabinet.
- The quality of the CFD validation in terms of agreement between the measured equilibrium concentrations and the CFD modelling results is not considered satisfactory enough. The model is useful to visualise which phenomena drive the transportation of hydrogen within the gas cabinet, but compared to the experiments, it lacks accurate predictive capabilities. Several reasons are possible, such as the effect of wind (gusts) or differences in temperature.

7.7 CFD recommendations

The following modelling recommendations are given with the ultimate aim of determining the design requirements of the gas station cabinet to keep hydrogen concentrations in the air below the LFL.

- A broader validation study based on academic cases is essential to find the cause of discrepancies between modelling and experiments up to this point. In other words, experiments conducted in a highly controlled environment (especially without wind) should be reproduced using the CFD modelling technique to distinguish modelling defects from errors due to the complexity of this particular case.
- Iterate different designs of vent openings to facilitate hydrogen outflow. Designs should be compatible with adequate protection of equipment inside.

8. Conclusions

The objective of this study was to gain insight into the suitability of ventilation of existing gas cabinets for hydrogen distribution. To gain that insight, the following sub-questions were posed:

1. Sub-question 1: What are the most obvious types of gas cabinets for the application of hydrogen distribution?
2. Sub-question 2: What conditions shall be met for a gas cabinet to be suitable for hydrogen distribution? [8]
3. Sub-question 3: To what extent do the most common gas cabinets meet the conditions, with or without additional ventilation? [9]

The first sub-question can be answered. There are three types of gas cabinets that reflect a substantial part of entire population: the HAS cabinet (or mini-cabinet), the ½ m3 cabinet and the 4 m3 cabinet station. These were selected after a survey with the network operators. This included gas cabinets installed in the last 10 years and an estimate of which type of gas cabinet will initially be used in a hydrogen network.

Data from the last 10 years show that recently mainly smaller gas cabinets have been installed, these gas cabinets are fairly uniform. In particular, 0.5m³ gas cabinets and 4m³ gas cabinet stations are largely comparable. This makes it plausible that the results from this study are a good indication for all stations of this volume, as long as they are similar with regard to the method of ventilation and the ventilation area. HAS cabinets (volume < 0.5 m³) are uniform to a lesser extent. Each grid operator has its own standard which sometimes differs a lot and sometimes just a little from the standard of other grid operators.

The second sub-question can also be answered, although this answer is more complex. The main condition is that (the housing of) a hydrogen gas station must be at least as safe as (the housing of) a natural gas station. To achieve this, care must be taken to ensure that the area freely accessible to the public can be designated as a Non Hazardous Area (NGG). For natural gas, within the gas cabinet of a gas station, an ATEX Zone 2 applies and immediately outside the gas cabinet the Non Hazardous Area begins. For this reason, no fencing is normally placed around a natural gas distribution station. The same should also apply to hydrogen stations. A gas cabinet (or: the gas cabinet including a shielded piece of ground surface) should be classifiable as an ATEX Zone 2. Then, immediately adjacent to this zone, ATEX zoning is no longer necessary and that area may be accessible to the general public.

To classify an area as ATEX zone 2, it must be possible to demonstrate that there is a secondary hazard source and that sufficient ventilation is present. This means that a flammable mixture may occur in less than 0.1% of the time. To demonstrate this, knowledge of leaks occurring in practice is needed. Leaks may occur at gas stations that lead to a concentration above 100% LEL/LFL, as long as they occur infrequently (< 0.1% of the time). After all, a thorough maintenance regime should ensure a technically tight installation by the owner.

This means that leaks that may occur 0.1% of the time or more frequently should not result in an ignitable mixture within the physical limits of the ATEX zone 2. On top of this, NPR7910-1 (2021) states that the ventilation rate must be greater than 5 times per hour. Also, this standard states, "In case of a

[8] The requirements for ventilation of current gas cabinets are laid down in NEN1059: 2019 and NEN12186: 2014 distinguishing between different types of gas cabinets. The selected leakage opening in NEN1059: 2019 is set at 1 mm² for zoning of set-up spaces. With the results from HyDelta 1.0, this leakage opening is in question for performing the tests within this work package (for testing ventilation and establishing zoning). In HyDelta 1.0, an explicit recommendation was made that there should be a difference between an incident and a regular leak/failure.

[9] In this research program, the starting point for the application of ventilation will first be based on existing gas cabinets and applicable standards. Modifications of the gas cabinets to improve ventilation will be determined in consultation where necessary.

small leakage, sufficient ventilation should be present to properly vent out the escaping gas" A practical interpretation of this is that the concentration should remain below the LEL/LFL.

It is important to state and substantiate a numerical value for this "small leakage". The above leads to the question of how large a leak can be that does occur 0.1% of the time or more frequently. Chapter 3 of this report takes a closer look at leakage openings and shows that several definitions of a "small leakage" are possible:

- NEN 1059: 2019 specifies a leakage opening of 1 mm²
- The IGEM/SR/25 mentions a leakage opening of 0.25 mm² (P > 100mbar) and 0.025 mm² (P < 100 mbar)
- The NEN-EN-IEC-60079-10-1 (2021) specifies a leakage opening in the range of 0.025 mm² to 0.25 mm².
- Practical measurements show that gas concentrations of 100% LEL or higher do not occur at the vent opening of district stations. Additional measurements with a hi-flow sampler also show that leaks greater than 40 l/h do not or hardly occur at natural gas-fueled stations. If we convert this flow rate (on the safe side) to hydrogen, a value of 125 l/h shall be used.

Within this study, measurements were made on leakages with openings of 0.25 mm² , 0.025 mm² and at a leakage rate of 40 l/h natural gas and 125 l/h hydrogen. In order to make a comparison between the safety level of natural gas and hydrogen stations, the latter leak openings should be looked at in particular, as they occur in practice.

All this leads to answering sub-question 3. Do the gas cabinets meet the conditions? Or, in other words, is the situation as safe with hydrogen compared to natural gas?

Measurement results ½ m3 cabinet

- For a 40l/h natural gas leak, the maximum gas concentration in a ½ m3 cabinet is about 1 vol%, a mixture below the lower flammability limit[10] . For a similar leak for hydrogen (125l/h), the concentration rises to 2.7 vol%, which is also below the lower flammability limit. Directly at the vent openings, similar concentrations are measured, with 3.2 vol% as a local, time-dependent outlier. Half a meter away from the gas cabinet, the concentration is well below the lower flammability limit in all cases.
- Measurements with leakage openings of 0.25 mm² and 0.025 mm² measured flammable mixtures with both natural gas and hydrogen.

Measurement results 4 m3 cabinet station

- For both natural gas (40l/h) and hydrogen (125 l/h), the concentration remains well below the lower flammability limit. The measured concentrations with hydrogen are higher, but in all cases below the limit of a combustible mixture.
- In measurements with leak openings of 0.25 mm² and 0.025 mm², no combustible mixture was measured with natural gas. In the case of hydrogen, a combustible mixture was measured at leak openings of 0.25 mm².

Measurement results mini-cabinet

- Some measurements were carried out at the mini-cabinet. These aimed to provide input to any follow-up research and are too limited to draw firm conclusions.
- An actual observation is that no combustible mixture was measured with natural gas (40l/h), while it was measured with hydrogen (125l/h).

Effects of adding extra ventilation

[10] With definition as added in glossary

The extent to which this particular ½ m3 cabinet could be modified to provide a larger ventilation area was then investigated. This involved measuring with leakage openings of 0.25 mm² and 0.025 mm². Adding additional ventilation area certainly has an effect, but not to the extent that it avoids all concentration above 100% LEL/LFL. Even when doubling the top ventilation (to 4% of the floor area) and additionally adding bottom ventilation (2% of the floor area), flammable mixtures of hydrogen continue to be formed when leakage flow rates in accordance with known values from the standards are applied. No measurements were made at a leakage flow rate of 125 l/h hydrogen because the concentration here already remained below 100% LEL/LFL with standard ventilation.

Another interesting insight from the tests with additional ventilation is the influence on the dispersion behavior of the gas mixture. For natural gas in particular, the gas concentration at the top of the casing becomes lower when additional ventilation is added, while for hydrogen the concentration at lower measurement points actually becomes lower. The explanation is that a hydrogen leak creates a "blanket" of a hydrogen/air mixture of similar concentration. This picture is confirmed by results of the CFD calculations. Adding extra ventilation does cause that blanket to become thinner but not to lower the concentration in that blanket. The effect is that extra ventilation does cause less gas to be present in the gas cabinet.

There is a strong suspicion that the configuration of the gas cabinet roof (the edge of the roof) leads to hydraulic resistance during ventilation, which is also one of the insights from the CFD calculations. As a result, both natural gas and hydrogen have insufficient opportunity to escape from the gas cabinet.

9. Recommendations

The following recommendations follow from this study:

- Consider incorporating concentration measurements into standard operating procedures by recording them for research and monitoring over longer periods. This can provide interesting insights into how populations of gas pressure regulating stations evolve.
- Consider adapting work instructions so that, when working on gas stations, technicians take a gas concentration measurement in the vent opening before opening the cabinet. Recording the measured gas concentration will give network operators more insight into actual frequency of occurrence of larger leaks with limited extra effort.
- The application of hydrogen at gas stations seems to require additional precautions to achieve the same level of safety as for natural gas. For the 4 m^3 cabinet station, this difference is more evident than for the ½m^3 cabinet. Based on the precautionary principle, for both the ½m^3 and the 4m3 cabinet station, additional precautionary measures are sensible. There are several possibilities here, such as further increasing the ventilation area of the casing, modifying the casing, placing fencing around at least one meter away from the casing or more intensive monitoring for leaks than is usual for natural gas stations.
- Further research on HAS cabinets is recommended before HAS cabinets are converted to hydrogen. Until that research is conducted, it is advisable to apply additional precautions when HAS cabinets are used for hydrogen. That research can be approached in two different ways. One possibility is to start from the existing situation, where each grid operator has its own standard gas cabinet. Each gas cabinet will then be investigated through CFD calculations and/or measurements. A second approach is to work towards a new design for gas cabinets of mini-cabinets. Then a number of concepts will be devised (in consultation with the constructors) and the effectiveness of these new concepts will be checked with CFD signification and/or measurements.
- It is important that the NEN 1059 standards committee makes a statement for which leakage flow rates (for which specific situation) ventilation should be an effective measure. Leakage rates and practical measurements still seem to be factors apart.

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I Overview of the composition of the EAG and sparring group

Table 9 - Composition of ESG/sparring group

Name	Employer	EAG	Sparring group
R. den Hartog	Westland	V	
F. Verweij	Westland		V
J. Jonkman	Rendo	V	
R. Scholten	Rendo	V	
P. Verstegen	Alliander	V	
R. Nispeling	Alliander		V
R. Verhoeve	Stedin	V	
J. Palmers	Coteq		V
J. Voogt	Enexis	V	
W. Koppenol	Enexis	V	
R. van Hooijdonk	Enexis		V
M. van der Laan	Kiwa Technology	V	
S. van Woudenberg	Kiwa Technology	V	
The sparring group is involved in reviewing the draft reports.			

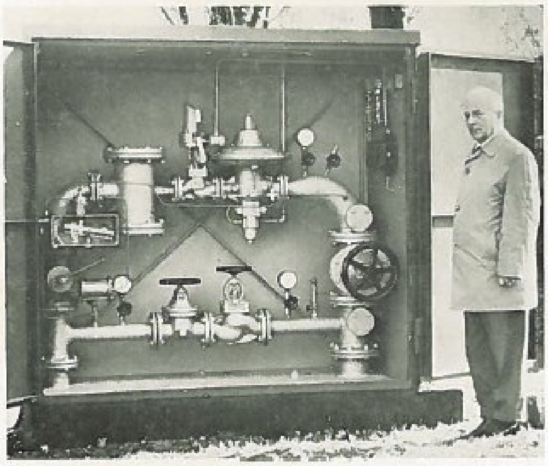
II Calculation of ventilation effects

3. Berekening van ventilatie-effecten

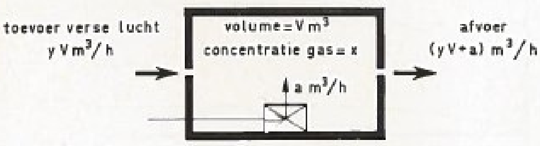
Helmann[1]) denkt zich een ruimte met een inhoud van V m³,

[1]) P. R. Helmann, Ingenieur Chef de Service au CERGA

Figuur 3 Kaststation voorzien van een hek



Figuur 4 Kaststation met geopende deuren, zodat de ingebouwde installatie is te zien (GAMOG, Zutphen)



Figuur 5 Schematische voorstelling van de ventilatie van een ruimte

waarin constant een hoeveelheid gas van a m³/h wordt gebracht. Het aantal malen dat een volume V verse lucht per uur wordt toegevoerd, stelt hij y, d.w.z. in een uur wordt aan het vertrek $y\,V$ m³ verse lucht toegevoerd en een volume van $(y\,V + a)$ m³ afgevoerd. Schematisch is dit voor te stellen als weergegeven in fig. 5.

Aangenomen dat de druk in de beschouwde ruimte gelijk blijft, kunnen wij de gasconcentratie x in deze ruimte na een tijd t berekenen door van de uitgestroomde gashoeveelheid af te trekken de hoeveelheid die is afgevoerd als gevolg van de ventilatie, dus:

$$V x = \int_0^t a\,dt - \int_0^t (y\,V + a)\,x\,dt$$

$$V x = at - (y\,V + a)\int_0^t x\,dt \quad \text{of}$$

$$\int_0^t x\,dt = -\frac{Vx - at}{yV + a} = \frac{at - Vx}{yV + a}$$

$$x = \frac{d}{dt}\,\frac{at - Vx}{yV + a} = \frac{1}{yV + a}\,\frac{d}{dt}\,(at - Vx)$$

$$x = \frac{a}{yV + a} - \frac{V}{yV + a}\,\frac{dx}{dt}.$$

Deze vergelijking is ook te schrijven als:

$$\frac{dx}{dt} + \frac{yV + a}{V}\,x - \frac{a}{V} = 0 \quad \ldots\ldots\ldots\ldots (1)$$

Wanneer wij voor $\frac{yV + a}{V} = p$ en voor $-\frac{a}{V} = q$ invullen,

dan krijgt de vergelijking de gedaante van een lineaire differentiaalvergelijking, nl.

$$\frac{dx}{dt} + px + q = 0.$$

De algemene oplossing hiervoor is:

$$x = e^{-\int pdt}\left(C_1 - qe^{\int pdt}\,dt\right) \quad \ldots\ldots\ldots\ldots (2)$$

die men kan schrijven als:

$$x = e^{-(pt + C_2)}\left(C_1 - q\int e^{pt + C_2}\,dt\right).$$

In deze vergelijking is $\int e^{pt + C_2}\,dt = \frac{1}{p}\,e^{pt + C_2} + C_3$

Stellen wij $C_1 - C_3\,q = C_4$, dan wordt de vergelijking:

$$x = e^{-(pt + C_2)}\left(C_4 - \frac{q}{p}\,e^{pt + C_2}\right),$$

of uitgewerkt:

$$x = C_4 e^{-(pt + C_2)} - \frac{q}{p}\,e^{-(pt + C_2)}\,.\,e^{pt + C_2}$$

$$x = C_4 e^{-(pt + C_2)} - \frac{q}{p} \quad \text{of}$$

$$x = C_4 e^{-C_2}\,.\,e^{-pt} - \frac{q}{p}.$$

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Wanneer wij $C_4\ e^{-C_2}$ vervangen door K, dan gaat de vergelijking over in:

$$x = K e^{-pt} - \frac{q}{p}.$$

Vullen wij nu weer de oorspronkelijke waarde van p en q in, dan gaat de vergelijking over in:

$$x = K e^{-\frac{yV + a}{V}t} + \frac{a}{yV + a} \quad \ldots\ldots\ldots\ldots (3)$$

Om de waarde voor K te vinden, gaan wij uit van de voorwaarde dat voor $t = 0$ ook $x = 0$ moet worden gevonden, waaruit volgt dat:

$$K = -\frac{a}{yV + a}$$

Wanneer wij deze waarde in de vergelijking 3 invullen, dan krijgen wij:

$$x = \frac{a}{yV + a}\left(1 - e^{-\frac{yV + a}{V}t}\right) \quad \ldots\ldots\ldots\ldots (4)$$

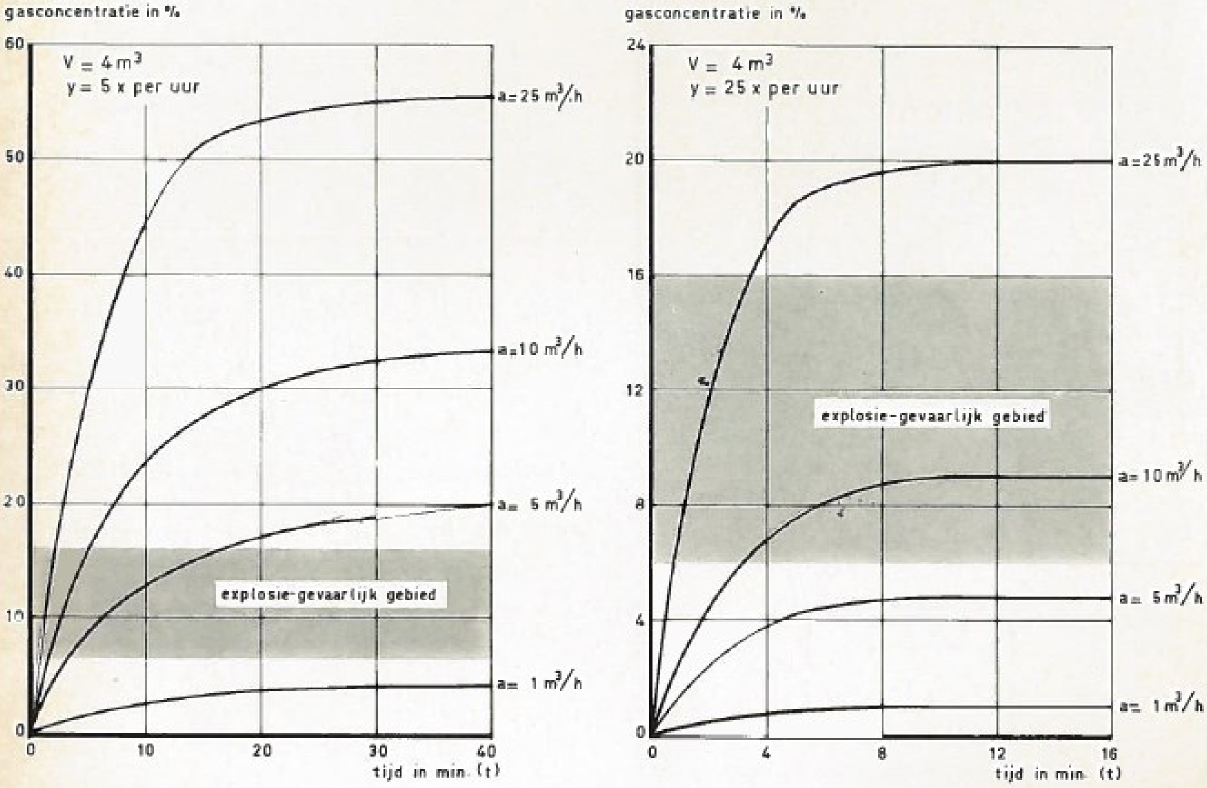
Wanneer wij voor t oneindig invullen, vinden wij de gasconcentratie in de eindtoestand en gaat formule 4 over in:

$$x = \frac{a}{yV + a} \quad \ldots\ldots\ldots\ldots (5)$$

Is het ventilatievoud gelijk aan nul, dan wordt x gelijk aan 1 (d.w.z. de gasconcentratie 100 %). Als a klein is t.o.v. yV, dan mogen wij stellen:

$$x = \frac{a}{yV} \quad \ldots\ldots\ldots\ldots (6)$$

Met vergelijking 4 kan men het verloop van de gasconcentratie met de tijd berekenen bij een bepaalde gasuitstroming in de ruimte en een bepaald ventilatievoud van die ruimte. De uitkomst van deze berekening is weergegeven in fig. 6 voor een ruimte met een inhoud van 4 m³ (gedacht is aan een kaststation), bij een ventilatievoud van 5 en een ventilatievoud van 25.
Bij een slechte ventilatie (5-voudig) in een kaststation kan met een gaslek van 1 m³/h de onderste explosiegrens niet worden bereikt, terwijl bij een lek van 5 m³/h na 15 min de bovenste explosiegrens al overschreden en het mengsel on-



Figuur 6 Het verloop van de gasconcentratie in een ruimte van 4 m³ met de tijd bij een uitstroming van 1 - 25 m³/h gas bij een 5-voudige en 25-voudige ventilatie

gevaarlijk wordt. Is de ventilatie normaal - waarmede wij een 20 - 25-voudige verversing van het volume per uur bedoelen - wordt, zoals wij zullen zien, bij een gaslek van 5 m³/h de onderste explosiegrens niet bereikt. Is het lek 25 m³/h, dan wordt na 3 min de bovenste explosiegrens reeds overschreden. Men bedenke wel dat bij de berekening steeds een volledige menging van gas en lucht is aangenomen.
Kortweg gezegd bereikt men bij een vergroting van het ventilatievoud van 5 naar 25, dat het gaslek mag toenemen van 1 naar 5 m³/h om nog net niet in het explosiegebied terecht te komen; m.a.w. men bereikt maar een kleine vergroting van de veiligheid door de toeneming van de ventilatie.
In fig. 7 is de berekening uitgevoerd voor een vertrek van 25 m³, waarbij gedacht is aan een keuken. Aan de linkerzijde is een ventilatievoud = 1 gekozen, d.w.z. een keuken waarbij men heeft gezorgd dat de ventilatie gering is (kieren dichtgestopt, ventilatie-openingen afgesloten). Ruwweg zien wij ook hier bij een vijfvoudige ventilatie dat er vijfmaal zoveel gas (5 m³/h) kan ontsnappen vóórdat sprake is van een gevaarlijke situatie in vergelijking met een enkelvoudige ventilatie. Bij een keuken is deze vergroting wel belangrijk, omdat de kans op ontsnapping van gas in hoeveelheden van 5 m³/h nog veel minder aannemelijk is dan bij een kaststation.

4. Oorzaken van ventilatie

De natuurlijke ventilatie wordt (in tegenstelling tot mechanische ventilatie) in het algemeen veroorzaakt door drie omstandigheden:

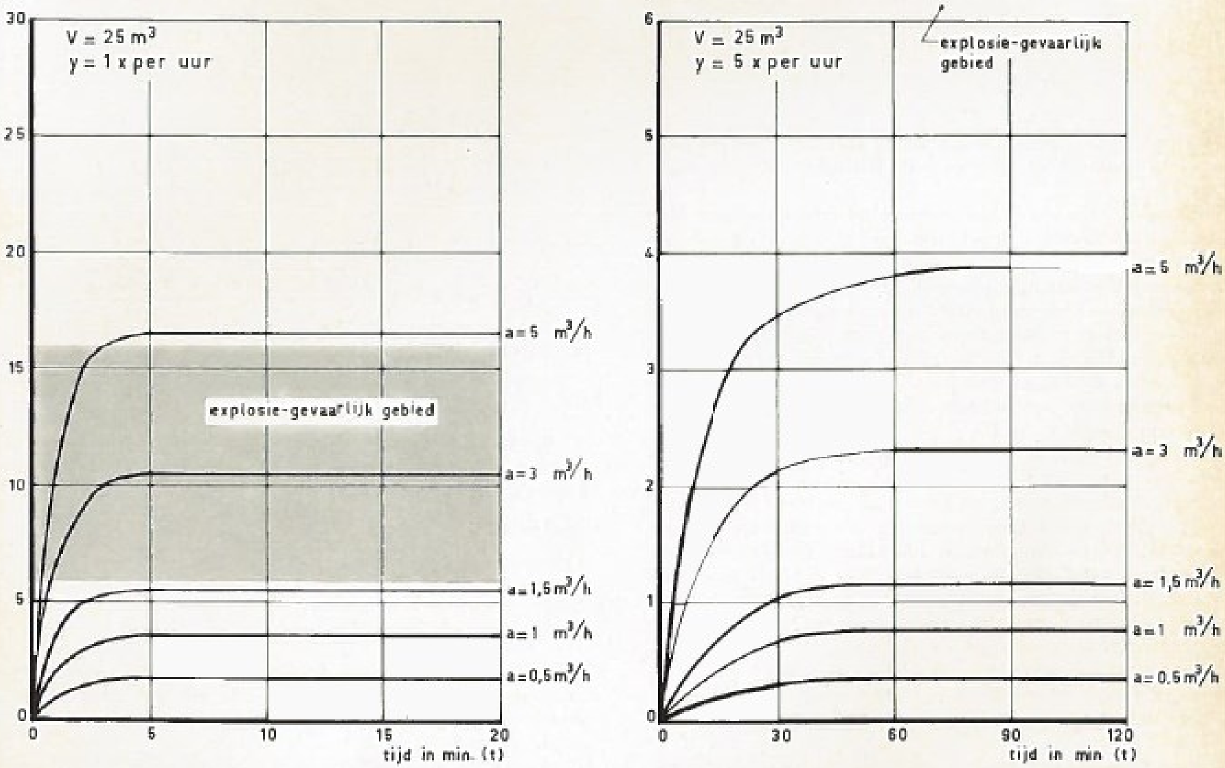
a. een verschil in druk voor de verschillende ventilatie-openingen als gevolg van windstromingen buiten de ruimte;

b. temperatuurverschillen tussen het gas of gas-luchtmengsel in de ruimte en die van de lucht daarbuiten;

c. verschil in soortelijke massa en gewicht tussen het gas of gas-luchtmengsel in de ruimte en die van de lucht daarbuiten.

5. Ventilatie door de wind

Ventilatie tengevolge van de wind is in het algemeen het belangrijkst bij een kaststation. Kaststations staan in Nederland bijna uitsluitend op de grond opgesteld tussen een min of meer dichte bebouwing. Derhalve wisselt de wind om zulk een station in de praktijk zeer sterk, zowel in grootte als in richting. Doordat in de kast een zekere demping optreedt van de buiten de kast voorkomende verschijnselen, schommelen de te meten waarden niet zo sterk. Met enig geduld en het herhalen van de metingen vindt men gemiddelde waarden, die meer dan voldoende nauwkeurig zijn ten aanzien



Figuur 7 Het verloop van de gasconcentratie in een ruimte van 25 m³ met de tijd bij een uitstroming van 1 - 5 m³/h bij een enkelvoudige en 5-voudige ventilatie

III Zoning

NPR-7910-1 (2021)
In the directive, a regular leakage at a gas station is classified as a secondary hazard source with the definition "a secondary hazard source is a hazard source from which the release of a flammable substance is not likely under normal operation, and if it does occur, infrequently and only for short periods of time" (see par 5.5.2 of NPR7910-1 (2021)). This includes less than 0.1% of the operating time of an installation or of the duration of an activity, the longest duration being decisive as named in the ATEX153 directive. Also, in the IGEM/SR/25 Edition 2 (2010) [5] Appendix 7 cites guideline numbers for component failure in gas pressure regulating stations. These quoted values are many times lower than 0.1% of operating time and may be considered short in that context. Of the Dutch situation, such data are not available for all network operators at the time of writing.

It should also be noted that the basis for the above situation is always an installation in operation (and therefore not during operations). During in operation, the following definition is given in NEN1059 (2019), section 7.3.11 a gas pressure regulation installation is a secondary hazard source. The installation must be technically gas-tight when put into operation and during operation. The set-up space of the gas pressure regulation installation is classified as hazard zone 1, or as hazard zone 2 if it can be shown that the ventilation rate of the set-up space exceeds 5 h^{-1} (classification according to NEN-EN-IEC 60079-10-1).

Besides determining the hazard source, ventilation also plays an important role. When ventilation is considered for a gas cabinet, this can be done using the NPR7910-1 (2021)(Dutch Practice Guideline - hazard zone classification with regard to explosion hazard) [22]. Section 8 (ventilation in the vicinity of a hazard source) evaluates what ventilation capacity a gas cabinet should have, according to Code of Practice. Here a distinction is made between moderate capacity (k = 0.25) and sufficient capacity (k = 0.1) where the relation to the percentage LEL/LFL is a measure for evaluating this capacity as described in section 8.4.2.2 of the NPR. It is also described here that "with sufficient capacity, hazard zone classifications do not take into account the likelihood of gas entrapment, as the conditions that may lead to this occur only rarely and then for a short period of time".

The calculation in NPR7910-1 (2021) consists of a concise roadmap.

In step 1, the required ventilation capacity of the gas cabinet is calculated (see 8.4).

$$VC = a \times \frac{100}{\mathrm{LEL}} \times \frac{100}{k}$$

With;

$$a = a_m \times \frac{1}{M} \times 25 \times 3{,}6$$

For moderate capacity, k equals 25% and for adequate capacity, k equals 10%. In this way, Step 1 includes an assessment of the LEL/LFL value (25% LEL or 10% LEL) for the ventilation requirement, what ventilation capacity is needed to ventilate a leakage flow rate back to 25% LEL or 10% LEL, respectively. It should be noted there that it is assumed that gas is uniformly diluted, which is described in section 8.4.2 of NPR7910.

In step 2, the required ventilation capacity is linked to the volume of the gas cabinet. This calculation should give a ventilation rate of the room that is greater than or equal to 5. The ventilation rate, i.e. the number of times the air is changed per hour (VV), is determined using the formula below;

$$VV = \frac{VC}{V}$$

When the ventilation rate VV is greater than 1 and less than 5, the ventilation capacity is considered moderate capacity (dilution up to 25% LEL/LFL possible). If the ventilation rate VV is greater than or equal to 5, then the ventilation capacity is considered adequate capacity (dilution up to 10% LEL/LFL possible). This classification mainly says something about the degree of dilution required in case of a leak, the locally prevailing concentration in and around the gas cabinet does not follow from this analysis. Nor does it follow from this analysis whether the built geometry of a gas cabinet is suitable for adequate ventilation. It merely lays down a requirement that the gas cabinet should meet.

Influence of wind and temperature
Natural ventilation is driven by a difference in pressure (inside and outside the gas cabinet) or a difference in concentration. This is referred to as convection or diffusion. Both processes occur relatively slowly and are more likely to be dominated by external factors such as wind and/or temperature. Ventilation can take place, for example, by wind blowing against the gas cabinet and changing the air inside the gas cabinet through the vent openings. The effective wind speed therefore affects the refreshment of air by natural draft.

In the aforementioned article from GAS [3] a conclusion was previously presented that ventilation of a cabinet station is largely wind-induced where the total area of the vent openings and the possibility of cross-ventilation are particularly important. It is also stated that the quality of ventilation is maximised when the ventilation openings are placed 5-10% of the cabinet height below the roof. If you place the vent openings too high, the cross wind will brush too much over the gas mixture in the cabinet and you need to multiply the area of the vent openings by a factor of 2 or 3 to get the same effect.

Also, a gas cabinet can ventilate due to a slight difference in temperature. On hot days, the temperature inside the gas cabinet is higher than in the outside air. This leads to a driving force that is many times smaller than through natural draught.

The effective wind speed can therefore be used to calculate the ventilation rate of air in the gas cabinet. By comparing the required ventilation rate (from the above calculation) with the practical ventilation rate, it can be determined whether the gas cabinet will ventilate sufficiently at a given wind speed. In NEN-EN-60079-10-1 (2021), the rule of thumb is 0.5 m/s for the wind velocity in both an obstructed and unobstructed area at a height of 2 meters or less above ground level (for gas and vapour emissions lighter than air).

Inside a gas cabinet, however, the effective wind speed inside the gas cabinet will be considerably lower. For this, using NEN-EN-60079-10-1 (2021), formula C.2 an estimate can be made that is around 0.1 to 0.2 m/s when the wind speed outside the gas cabinet is 0.5 m/s. In NEN1059;2019, the rule of thumb is that the available ventilation area for cabinets/cabinet stations should be at least 2% of the floor area. From other standards such as EN12186;2014, a reference value of only 1% of the floor area is mentioned. Based on the wind speed and the available ventilation area, it can be determined how often a gas cabinet content can be refreshed per unit time. This is the combination of ventilation capacity (what is needed) and effective wind speed (what is available).

This calculation was made for the 1/2m³ cabinet in Appendix IV for different leakage rates at natural gas and hydrogen. The result of this calculation is a judgement on the geometry based on ventilation capacity (what is minimally required to reduce the concentration below 25% LEL/LFL or 10% LEL/LFL) at a specific leakage. The colour code green indicates that the gas cabinet can theoretically ventilate sufficiently at the stated leakages, the colour orange indicates that it cannot ventilate sufficiently at those conditions. These values can be compared with experiments to see if this is an approximate match.

Also, with the above data (the type of leakage and the quality of ventilation), based on section 9.4 from NPR7910 (2021), Table 7, it is possible to determine the zoning belonging to the considered situation.

In the case of a leak from a secondary source in a closed building with limited ventilation according to section 8.4.2 and moderate capacity (1 ≤ VV ≤ 5), this situation leads to an ATEX zoning 2. The same applies when sufficient capacity (VV ≥ 5) is available where the size of the zone will in all cases cover the entire inside of a pressure regulator station[11] .

In this, the approach to natural gas compared to hydrogen differs only in the fact that the flammability limits are different and that the outflow of gas in the event of a leakage will be greater for hydrogen compared to natural gas which will also result in different zone dimensions. No research is available for this at the time of writing.

Changing the zoning will only have to take place when the classification of the source changes from secondary to primary. It is also possible to look at applying a zone 2 NE (negligible extent) where the classification is downgraded to a negligible risk. However, it is then assumed that a gas station is always technically tight, where previous research [8] has shown that this is not feasible in practice.

Relationship between safety distances and ATEX zoning

Section 6.2 of NEN 1059-2019 defines safety distances for all categories of gas stations in relation to vulnerable and limited vulnerable objects. The question of whether and how these safety distances should be adjusted for hydrogen-driven stations is beyond the scope of this study.

[11] The distances mentioned in Table 7 apply at leakage rates between 1 gram and 10 grams per second. These values mainly refer to the current situation with natural gas and will have to be reconsidered in the future with hydrogen.

NEN-EN-IEC-60079-10-1 (2021)
The NEN-EN-IEC-60079-10-1 (2021)(Explosive atmospheres - Part 10-1: Classification of areas - explosive gas atmospheres) contains a detailed description for the zone determination of a technical installation. Here, calculations are presented which, where possible, are complemented by practical experience (or measured values) if available.

Appendices C and D of this international standard describe in steps how to perform such an analysis. A typical analysis consists of the following steps;

- ✓ Determine the type of leakage source (continuous/ primary/ secondary).
- ✓ Determine the leakage rate of the leakage source.
- ✓ Determine the degree of dilution based on leakage rate and ventilation.
- ✓ Determine the corresponding ATEX zoning based on the degree of dilution, the availability of ventilation (reliability) and the type of leak source.

Using these steps, the zone determination of a gas pressure regulating station was carried out. The steps are numbered to provide a clear link to the list above, which can thus be used as a checklist.

Step 1; for natural gas and hydrogen leaks, a secondary leakage source is assumed ("a secondary hazard source is a hazard source from which the release of a flammable substance is not likely under normal operation, and if it does occur, not frequently and only for short periods of time").

Step 2; for natural gas and hydrogen we choose a small leakage for a moment, so for example a leakage source of 0.025 mm² at a supply pressure of 8 bar. This leads to a leakage rate of 0.18 m^3_n /h natural gas and 0.56 m^3_n /h hydrogen.

Normally, an estimate of the degree of dilution in the casing would be made in step 3 using Figure C.1 from NEN-EN-IEC-60079-10-1 (2021). Based on experiments, we will learn that in the event of a leakage of natural gas (or hydrogen) at 0.025 mm² at a pressure of 8 bar, the concentrations in the 1/2m³ casing increase to 6.0 vol% (for natural gas) and 6.9 vol% (for hydrogen), respectively.

Section 3.6.2 of the standard states that the degree of dilution should be considered low if the background concentration exceeds 25% of the LEL/LFL. The next step in the process is to make a judgement on the availability of ventilation.

The quality of ventilation is influenced by the geometry of the gas cabinet. For this purpose, a numerical value for the ventilation inefficiency is added (the f-value). The ventilation inefficiency is the degree to which the air in the gas cabinet is well mixed outside the sphere of influence of the leakage opening.

f=1: the background concentration is uniform and the leakage opening is far away from the vent openings, so the concentration at the vent openings represents the average background concentration.

f>1: there is a gradient of background concentration in the gas cabinet due to inefficient mixing and the vent is "far" from the leakage itself, so the concentration at the outlet is smaller than the average background concentration. The value of f can be between 1.5 for slightly inefficient mixing and 5 for very inefficient mixing. This factor corrects for non-uniformity in airflow patterns in a gas cabinet with obstacles where vent openings are not optimally positioned for maximum ventilation effect.

Previous experiments in HyDelta have shown that the gas concentration present in a gas cabinet varies. A concentration gradient is present that increases with the vertical position in the gas cabinet for many of the measurements performed. The ventilation inefficiency will therefore have to be estimated as high for the 1/2m³ gas cabinet.

When table D.1 "Zones for grade of release and effectiveness of ventilation" from NEN-EN-IEC-60079-10-1 (2021) is consulted, it shows that with strict adherence to the method and the results from the experiments, it should be concluded that the degree of dilution is low (the background concentration is higher than 25% of the LEL/LFL) where an ATEX zone 1 should be assigned. The key to success here lies in improving ventilation and moving to the left in the table below.

Grade of release	Effectiveness of Ventilation						
	High Dilution			Medium Dilution			Low Dilution
	Availability of ventilation						
	Good	Fair	Poor	Good	Fair	Poor	Good, fair or poor
Continuous	Non-hazardous (Zone 0 NE)[a]	Zone 2 (Zone 0 NE)[a]	Zone 1 (Zone 0 NE)[a]	Zone 0	Zone 0 + Zone 2[c]	Zone 0 + Zone 1	Zone 0
Primary	Non-hazardous (Zone 1 NE)[a]	Zone 2 (Zone 1 NE)[a]	Zone 2 (Zone 1 NE)[a]	Zone 1	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1 or zone 0[c]
Secondary[b]	Non-hazardous (Zone 2 NE)[a]	Non-hazardous (Zone 2 NE)[a]	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 and even Zone 0[d]

[a] Zone 0 NE, 1 NE or 2 NE indicates a theoretical zone which would be of negligible extent under normal conditions.

[b] The Zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

[c] Zone 1 is not needed here. I.e. small Zone 0 is in the area where the release is not controlled by the ventilation and larger Zone2 for when ventilation fails.

[d] Will be Zone 0 if the ventilation is so weak and the release is such that in practice an explosive gas atmosphere exists virtually continuously (i.e. approaching a 'no ventilation' condition).

'+' signifies 'surrounded by'.

Availability of ventilation in naturally ventilated enclosed spaces is commonly not considered as good.

This whole reasoning hinges on choosing the leakage rate and defining a realistic leakage. Studies on leaks at gas stations show that in practice leaks are smaller than those mentioned in standards [10] [9]. So for these specific leakage rates, the conclusion could be different. This is an important part of this study, what choice leads to what consequences and what do we currently know from practice.

IV Calculation of ventilation rate of tested gas cabinets

1/2m³ cabinet - natural gas at 0.025 mm leakage opening

Afmetingen kast			Inputs		
Lengte	1000	[mm]	k1 (NPR)	10	%
Breedte	500	[mm]	k2 (NPR)	25	%
Hoogte	1000	[mm]	LEL (aardgas)	5,0	vol%
			M (aardgas)	18,636	[g/mol]
Inhoud - bruto	0,5000	[m3]	Windsnelheid	0,5	[m/s]
Af	0,0750	[m3]	Gehinderde windsnelheid, 20% effectief	0,1	[m/s]
Inhoud - netto	0,4250	[m3]			
Vloeroppervlak	0,5	[m2]	Aard van lekkage volgens NPR7910	secundair	
Ventilatie	2,0%		ATEX zonering volgens tabel 7, NPR7910	zone 2	
Ventilatie oppervlak	0,01	[m2]			

Berekeningen	0,025 [mm2] bij 8 [bar]			0,025 [mm2] bij 1 [bar]	
WINDLUW					
Lekopening	0,025	[mm2]	Lekopening	0,025	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,04139	[g/s]	Lekdebiet (a_m)	0,00917	[g/s]
Lekdebiet (a)	0,17889	[m3/h(n)]	Lekdebiet (a)	0,03996	[m3/h(n)]
VC (25%) - minimaal nodig	14,31	(gematigd)	VC (25%) - minimaal nodig	3,1968	(gematigd)
VC (10%) - minimaal nodig	35,78	(goed)	VC (10%) - minimaal nodig	7,992	(goed)
Gehinderde windsnelheid, 20% effectief	0,10	[m/s]	Gehinderde windsnelheid, 20% effectief	0,10	[m/s]
Ventilatiecapaciteit obv windsnelheid	3,6		Ventilatiecapaciteit obv windsnelheid	3,6	
Ventilatievoud (Vv)	8,5		Ventilatievoud (Vv)	8,5	
Wat is minimaal nodig als VC (voor 25% LEL)	14,3	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	3,2	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	35,8	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	8,0	(goed)
Welke Vv is beschikbaar obv windsnelheid	8,5		Welke Vv is beschikbaar obv windsnelheid	8,5	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Ja	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Ja	
Concentratie in behuizing (experiment)	6,0%	(max)	Concentratie in behuizing (experiment)	1,0%	(max)

WIND bij 0,5m/s					
Lekopening	0,025	[mm2]	Lekopening	0,025	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,04139	[g/s]	Lekdebiet (a_m)	0,00917	[g/s]
Lekdebiet (a)	0,17889	[m3/h(n)]	Lekdebiet (a)	0,03996	[m3/h(n)]
VC (25%) - minimaal nodig	14,31	(gematigd)	VC (25%) - minimaal nodig	3,1968	(gematigd)
VC (10%) - minimaal nodig	35,78	(goed)	VC (10%) - minimaal nodig	7,992	(goed)
Windsnelheid	0,50	[m/s]	Windsnelheid	0,50	[m/s]
Ventilatiecapaciteit obv windsnelheid	18,0		Ventilatiecapaciteit obv windsnelheid	18,0	
Ventilatievoud (Vv)	42,4		Ventilatievoud (Vv)	42,4	
Wat is minimaal nodig als VC (voor 25% LEL)	14,3	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	3,2	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	35,8	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	8,0	(goed)
Welke Vv is beschikbaar obv windsnelheid	42,4		Welke Vv is beschikbaar obv windsnelheid	42,4	
Is de Vv voldoende voor minder dan 25% LEL ?	Ja		Is de Vv voldoende voor minder dan 25% LEL ?	Ja	
Is de Vv voldoende voor minder dan 10% LEL ?	Ja		Is de Vv voldoende voor minder dan 10% LEL ?	Ja	

1/2m³ cabinet - natural gas at 0.25 mm leakage opening

Afmetingen kast			Inputs		
Lengte	1000	[mm]	k1 (NPR)	10	%
Breedte	500	[mm]	k2 (NPR)	25	%
Hoogte	1000	[mm]	LEL (aardgas)	5,0	vol%
			M (aardgas)	18,636	[g/mol]
Inhoud - bruto	0,5000	[m3]	Windsnelheid	0,5	[m/s]
Af	0,0750	[m3]	Gehinderde windsnelheid, 20% effectief	0,1	[m/s]
Inhoud - netto	0,4250	[m3]			
Vloeroppervlak	0,5	[m2]	Aard van lekkage volgens NPR7910	secundair	
Ventilatie	2,0%		ATEX zonering volgens tabel 7, NPR7910	zone 2	
Ventilatie oppervlak	0,01	[m2]			

Berekeningen	0,25 [mm2] bij 8 [bar]			0,25 [mm2] bij 1 [bar]	
WINDLUW					
Lekopening	0,25	[mm2]	Lekopening	0,25	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,41389	[g/s]	Lekdebiet (a_m)	0,09167	[g/s]
Lekdebiet (a)	1,78890	[m3/h(n)]	Lekdebiet (a)	0,3996	[m3/h(n)]
VC (25%) - minimaal nodig	143,11	(gematigd)	VC (25%) - minimaal nodig	31,97	(gematigd)
VC (10%) - minimaal nodig	357,78	(goed)	VC (10%) - minimaal nodig	79,92	(goed)
Gehinderde windsnelheid, 20% effectief	0,10	[m/s]	Gehinderde windsnelheid, 20% effectief	0,10	[m/s]
Ventilatiecapaciteit obv windsnelheid	3,6		Ventilatiecapaciteit obv windsnelheid	3,6	
Ventilatievoud (Vv)	8,5		Ventilatievoud (Vv)	8,5	
Wat is minimaal nodig als VC (voor 25% LEL)	143,1	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	32,0	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	357,8	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	79,9	(goed)
Welke Vv is beschikbaar obv windsnelheid	8,5		Welke Vv is beschikbaar obv windsnelheid	8,5	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Nee	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Nee	
Concentratie in behuizing (experiment)	26,6%	(max)	Concentratie in behuizing (experiment)	11,9%	(max)

WIND bij 0,5m/s					
Lekopening	0,25	[mm2]	Lekopening	0,25	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,04139	[g/s]	Lekdebiet (a_m)	0,00917	[g/s]
Lekdebiet (a)	1,78890	[m3/h(n)]	Lekdebiet (a)	0,3996	[m3/h(n)]
VC (25%) - minimaal nodig	143,11	(gematigd)	VC (25%) - minimaal nodig	31,97	(gematigd)
VC (10%) - minimaal nodig	357,78	(goed)	VC (10%) - minimaal nodig	79,92	(goed)
Windsnelheid	0,50	[m/s]	Windsnelheid	0,50	[m/s]
Ventilatiecapaciteit obv windsnelheid	18,0		Ventilatiecapaciteit obv windsnelheid	18,0	
Ventilatievoud (Vv)	42,4		Ventilatievoud (Vv)	42,4	
Wat is minimaal nodig als VC (voor 25% LEL)	143,1	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	32,0	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	357,8	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	79,9	(goed)
Welke Vv is beschikbaar obv windsnelheid	42,4		Welke Vv is beschikbaar obv windsnelheid	42,4	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Ja	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Nee	

1/2m³ cabinet - hydrogen at 0.025 mm leakage opening

Afmetingen kast			**Inputs**		
Lengte	1000	[mm]	k1 (NPR)	10	%
Breedte	500	[mm]	k2 (NPR)	25	%
Hoogte	1000	[mm]	LEL (waterstof)	4,0	vol%
			M (waterstof)	2,016	[g/mol]
Inhoud - bruto	0,5000	[m3]	Windsnelheid	0,5	[m/s]
Af	0,0750	[m3]	Gehinderde windsnelheid, 20% effectief	0,1	[m/s]
Inhoud - netto	0,4250	[m3]			
Vloeroppervlak	0,5	[m2]	Aard van lekkage volgens NPR7910	secundair	
Ventilatie	2,0%		ATEX zonering volgens tabel 7, NPR7910	zone 2	
Ventilatie oppervlak	0,01	[m2]			

Berekeningen	0,025 [mm2] bij 8 [bar]			0,025 [mm2] bij 1 [bar]	
WINDLUW					
Lekopening	0,025	[mm2]	Lekopening	0,025	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,01389	[g/s]	Lekdebiet (a_m)	0,00306	[g/s]
Lekdebiet (a)	0,55800	[m3/h(n)]	Lekdebiet (a)	0,12500	[m3/h(n)]
VC (25%) - minimaal nodig	55,80	(gematigd)	VC (25%) - minimaal nodig	12,5	(gematigd)
VC (10%) - minimaal nodig	139,50	(goed)	VC (10%) - minimaal nodig	31,25	(goed)
Gehinderde windsnelheid, 20% effectief	0,10	[m/s]	Gehinderde windsnelheid, 20% effectief	0,10	[m/s]
Ventilatiecapaciteit obv windsnelheid	3,6		Ventilatiecapaciteit obv windsnelheid	3,6	
Ventilatievoud (Vv)	8,5		Ventilatievoud (Vv)	8,5	
Wat is minimaal nodig als VC (voor 25% LEL)	55,8	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	12,5	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	139,5	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	31,3	(goed)
Welke Vv is beschikbaar obv windsnelheid	8,5		Welke Vv is beschikbaar obv windsnelheid	8,5	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Nee	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Nee	

WIND bij 0,5m/s					
Lekopening	0,025	[mm2]	Lekopening	0,025	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,01389	[g/s]	Lekdebiet (a_m)	0,00306	[g/s]
Lekdebiet (a)	0,55800	[m3/h(n)]	Lekdebiet (a)	0,12500	[m3/h(n)]
VC (25%) - minimaal nodig	55,80	(gematigd)	VC (25%) - minimaal nodig	12,5	(gematigd)
VC (10%) - minimaal nodig	139,50	(goed)	VC (10%) - minimaal nodig	31,25	(goed)
Windsnelheid	0,50	[m/s]	Windsnelheid	0,50	[m/s]
Ventilatiecapaciteit obv windsnelheid	18,0		Ventilatiecapaciteit obv windsnelheid	18,0	
Ventilatievoud (Vv)	42,4		Ventilatievoud (Vv)	42,4	
Wat is minimaal nodig als VC (voor 25% LEL)	55,8	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	12,5	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	139,5	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	31,3	(goed)
Welke Vv is beschikbaar obv windsnelheid	42,4		Welke Vv is beschikbaar obv windsnelheid	42,4	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Ja	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Ja	

1/2m³ cabinet - hydrogen at 0.25 mm leakage opening

Afmetingen kast			**Inputs**		
Lengte	1000	[mm]	k1 (NPR)	10	%
Breedte	500	[mm]	k2 (NPR)	25	%
Hoogte	1000	[mm]	LEL (waterstof)	4,0	vol%
			M (waterstof)	2,016	[g/mol]
Inhoud - bruto	0,5000	[m3]	Windsnelheid	0,5	[m/s]
Af	0,0750	[m3]	Gehinderde windsnelheid, 20% effectief	0,1	[m/s]
Inhoud - netto	0,4250	[m3]			
Vloeroppervlak	0,5	[m2]	Aard van lekkage volgens NPR7910	secundair	
Ventilatie	2,0%		ATEX zonering volgens tabel 7, NPR7910	zone 2	
Ventilatie oppervlak	0,01	[m2]			

Berekeningen 0,25 [mm2] bij 8 [bar] — 0,25 [mm2] bij 1 [bar]

WINDLUW

Lekopening	0,25	[mm2]	Lekopening	0,25	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,13944	[g/s]	Lekdebiet (a_m)	0,03111	[g/s]
Lekdebiet (a)	5,58000	[m3/h(n)]	Lekdebiet (a)	1,25000	[m3/h(n)]
VC (25%) - minimaal nodig	558,00	(gematigd)	VC (25%) - minimaal nodig	125	(gematigd)
VC (10%) - minimaal nodig	1395,00	(goed)	VC (10%) - minimaal nodig	312,5	(goed)
Gehinderde windsnelheid, 20% effectief	0,10	[m/s]	Gehinderde windsnelheid, 20% effectief	0,10	[m/s]
Ventilatiecapaciteit obv windsnelheid	3,6		Ventilatiecapaciteit obv windsnelheid	3,6	
Ventilatievoud (Vv)	8,5		Ventilatievoud (Vv)	8,5	
Wat is minimaal nodig als VC (voor 25% LEL)	558,0	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	125,0	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	1395,0	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	312,5	(goed)
Welke Vv is beschikbaar obv windsnelheid	8,5		Welke Vv is beschikbaar obv windsnelheid	8,5	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Nee	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Nee	
Concentratie in behuizing (experiment)	24,0%	(max)	Concentratie in behuizing (experiment)	11,0%	(max)

WIND bij 0,5m/s

Lekopening	0,25	[mm2]	Lekopening	0,25	[mm2]
Druk	8	[bar]	Druk	1	[bar]
Flow	Sonic		Flow	Sonic	
Formula for flow correct ?	VALID			VALID	
Lekdebiet (a_m)	0,13944	[g/s]	Lekdebiet (a_m)	0,03111	[g/s]
Lekdebiet (a)	5,58000	[m3/h(n)]	Lekdebiet (a)	1,25000	[m3/h(n)]
VC (25%) - minimaal nodig	558,00	(gematigd)	VC (25%) - minimaal nodig	125	(gematigd)
VC (10%) - minimaal nodig	1395,00	(goed)	VC (10%) - minimaal nodig	312,5	(goed)
Windsnelheid	0,50	[m/s]	Windsnelheid	0,50	[m/s]
Ventilatiecapaciteit obv windsnelheid	18,0		Ventilatiecapaciteit obv windsnelheid	18,0	
Ventilatievoud (Vv)	42,4		Ventilatievoud (Vv)	42,4	
Wat is minimaal nodig als VC (voor 25% LEL)	558,0	(gematigd)	Wat is minimaal nodig als VC (voor 25% LEL)	125,0	(gematigd)
Wat is minimaal nodig als VC (voor 10% LEL)	1395,0	(goed)	Wat is minimaal nodig als VC (voor 10% LEL)	312,5	(goed)
Welke Vv is beschikbaar obv windsnelheid	42,4		Welke Vv is beschikbaar obv windsnelheid	42,4	
Is de Vv voldoende voor minder dan 25% LEL ?	Nee		Is de Vv voldoende voor minder dan 25% LEL ?	Nee	
Is de Vv voldoende voor minder dan 10% LEL ?	Nee		Is de Vv voldoende voor minder dan 10% LEL ?	Nee	

V Photos of the test setup

Figure 53. The ½ m3 cabinet in an outdoor situation

Figure 54. The ½ m3 cabinet containing the gas control station

Figure 55. The 4m³ cabinet station in an outdoor situation

Figure 56. The 4m³ cabinet station containing the PRS

Figure 57. The HAS cabinet in an outdoor situation

Figure 58. The HAS cabinet containing the high-pressure delivery station

Figure 59. Set of nozzles with different diameters

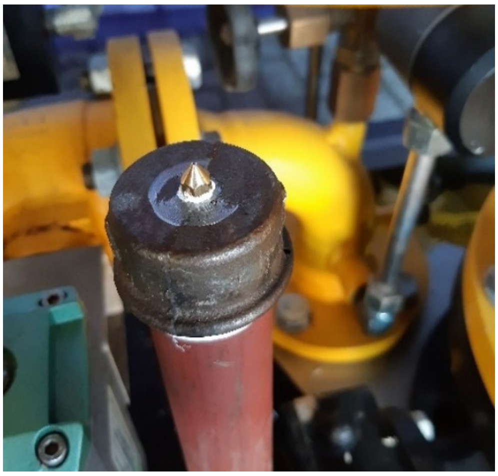


Figure 60. Nozzle with 0.25 mm leakage opening in the 1/2m³ casing

Figure 61. MultiRAE Lite IR Natural gas detector

Figure 62. Riken Keiki NP 1000 Hydrogen detector

VI Measuring equipment used

Table 10 - Measuring equipment used details

Description	Make and type	Kiwa number
Natural gas detector	MultiRAE - Lite IR	114033
Natural gas detector	MultiRAE Lite IR	114034
Natural gas detector	MultiRAE Lite IR	114036
Natural gas detector	MultiRAE Lite IR	114037
Natural gas detector	MultiRAE Lite IR	114038
Natural gas detector	MultiRAE Lite IR	114039
Natural gas detector	MultiRAE Lite IR	114040
Natural gas detector	MultiRAE Lite IR	114041
Natural gas detector	MultiRAE Lite IR	114043
Hydrogen detector	Riken Keiki NP 1000	-
MFC (natural gas/hydrogen)	Bronkhorst, type F-201CV-RAD-22-V	-
MFC (natural gas/hydrogen)	Bronkhorst, Type F-203AV-M50-RBD-FF-V	-

Natural gas
- The Multirae have a measurement range of 0 - 100% LEL/LFL and 0-100vol% natural gas).
- The four Multirae sensors used as measuring points at a greater distance (at 0.5m and 1m downwind) from the gas pressure regulating station have a measurement range of 0 - 100% LEL/LFL and 0-100vol% natural gas.

Hydrogen
- The Riken Keiki sensors have a measurement range of 0 - 100 vol% hydrogen.
- The four Multirae sensors used as measuring points at a greater distance (at 0.5m and 1m downwind) from the gas pressure regulating station have a measurement range of 0-1000 ppm hydrogen. Also, these specific Multirae sensors are equipped with a 0 - 100% LEL/LFL sensor for hydrogen.

VII Overview of all measurements

1/2m³ cabinet

Table 6 - 1/2m³ cabinet results - windless situation for natural gas (top) and hydrogen (bottom). LEL/LFL natural gas ≥ 5 vol% and LEL/LFL hydrogen ≥ 4 vol%. Outside the gas cabinet was measured at 0.5 m distance.

Aardgas/ natural gas		1/2m3 kast						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,179	8	6,0%	6,0%	6,0%	2,0%	0,1%	-	100
0,04	1	1,0%	1,0%	0,5%	0,1%	0,4%	-	-
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
1,8 *	8	26,6%	21,5%	25,1%	2,7%	23,1%	7,0%	>1000
0,4	1	11,9%	11,3%	11,6%	4,0%	10,8%	-	-

Waterstof/ hydrogen		1/2m3 kast						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,558	8	6,9%	6,3%	6,4%	4,5%	6,4%	-	580
0,125	1	2,7%	2,9%	2,6%	1,4%	3,2%	-	260
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
5,8	8	24,0%	20,0%	20,0%	18,0%	21,0%	18,0%	>1000
1,25	1	11,0%	10,0%	11,0%	6,5%	11,0%	-	580

*) leakage produces natural gas concentrations above the UEL but because there will always be a transition in concentration somewhere within the flammability limits of the gas, these values are shown in red.

4m³ cabinet station

Table 7 - 4m³ cabinet station results - windless situation for natural gas (top) and hydrogen (bottom). LEL/LFL natural gas ≥ 5 vol% and LEL/LFL hydrogen ≥ 4 vol%. Outside gas cabinet was measured at 0.5 m distance.

Aardgas/ natural gas		4m3 kaststation						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,179	8	0,8%	0,2%	0,7%	0,4%	0,4%	-	-
0,04	1	0,1%	0,0%	0,0%	0,0%	0,1%	-	-
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
1,8	8	4,3%	2,6%	1,0%	3,7%	3,7%	-	-
0,4	1	1,1%	0,9%	0,3%	0,5%	1,8%	-	-

Waterstof/ hydrogen		4m3 kaststation						
Lekopening 0,025 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
0,558	8	2,2%	0,9%	1,6%	1,1%	1,3%	-	70
0,125	1	1,0%	0,3%	0,4%	0,4%	0,4%	-	10
Lekopening 0,25 mm^2								
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening				op 0,5 m	
nm3/hr	bar	vol%	vol%					
			N	O	Z	W	%LFL	ppm
5,8	8	12,0%	9,1%	4,0%	9,3%	6,0%	-	570
1,25	1	5,5%	4,1%	4,0%	3,6%	4,1%	-	120

HAS cabinet

The capacity of the HAS cabinet is approximately 0.06 m³. Only measured with 0.025 mm², no data available for the leakage gap of 0.25 mm².

Table 8 - HAS cabinet results - windless situation for natural gas (top) and hydrogen (bottom). LEL/LFL natural gas ≥5 vol% and LEL/LFL hydrogen ≥4 vol%. Outside the gas cabinet was measured at 0.5 m distance.

Aardgas/ natural gas		HAS kast				
Lekopening 0,025 mm^2						
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening		op 0,5 m	
nm3/hr	bar	vol%	vol%			
			Links	Rechts	%LFL	ppm
0,179	8	10,3%	9,1%	7,9%	0,0%	0
0,04	1	3,3%	3,9%	2,7%	0,0%	0

Waterstof/ hydrogen		HAS kast				
Lekopening 0,025 mm^2						
Lekdebiet	Druk	Max concentratie behuizing	Max concentratie ventilatieopening		op 0,5 m	
nm3/hr	bar	vol%	vol%			
			Links	Rechts	%LFL	ppm
0,558 *	8	12,0%	12,0%	12,0%	0,0%	410
0,125	1	4,8%	5,6%	4,1%	0,0%	20
** experiment voortijdig gestopt (ivm veiligheid) door snelle opbouw van waterstof concentratie.*						

VIII Measurement results - ½ m^3 cabinet

Leakage rate 1.8 m^3_n /hr - natural gas (leakage opening 0.25 mm^2) - 8 bar

At a leak rate of 1.8 m^3_n /h, the natural gas concentration in the ½ m^3 gas cabinet rises to a maximum concentration of 13 vol%. The test is shorter than other tests due to the significant gas concentration that builds up in the casing in a short time. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, a small influence of wind was observed creating preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

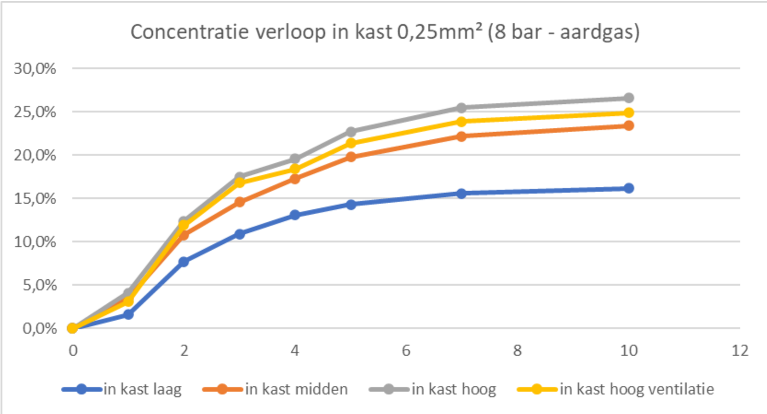


Figure 63. Concentration (vol % CH4) in the ½ m³ cabinet at a leakage rate of 1.8 m³(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	21.5vol%	25.1vol%	2.7vol%	23.1vol%

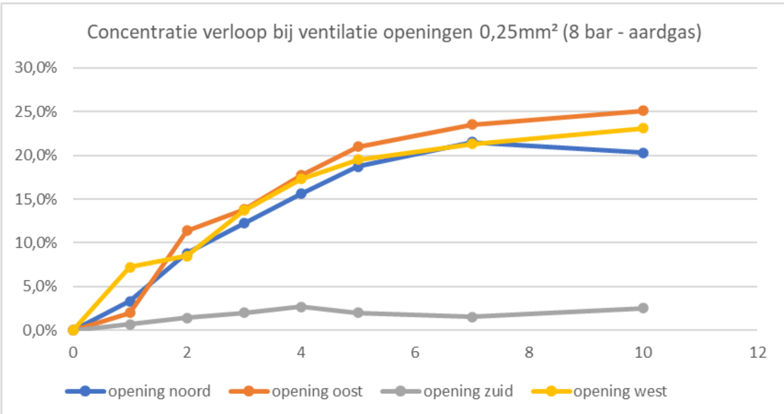


Figure 64. Concentration (vol% CH_4) at the vent openings of a ½ m3 cabinet at a leakage rate of 1.8 m3(n)/h

During the experiment, the concentration of natural gas outside the gas pressure regulating station occasionally rises to a maximum of 7% LEL/LFL. This concentration is measured 0.5 meters (west) away from the gas cabinet at a height of 1 meter from the ground.

Leakage rate 5.6 m^3_n /hr - hydrogen (leakage opening 0.25 mm²) - 8 bar

When a hydrogen leak was created with the same pressure, the measured leakage flow rate was about 5.6 m^3_n /h. This leak led to a hydrogen concentration of up to 22 vol% in the casing. The test is shorter than other tests due to the significant gas concentration that builds up in the casing in a short time. The influence of wind was only considered if it interfered with experiments in the windless situation. No influence was observed during this measurement. The graph below shows the concentration of hydrogen as a function of time in minutes. Due to the high concentration, the experiment was stopped after a short time.

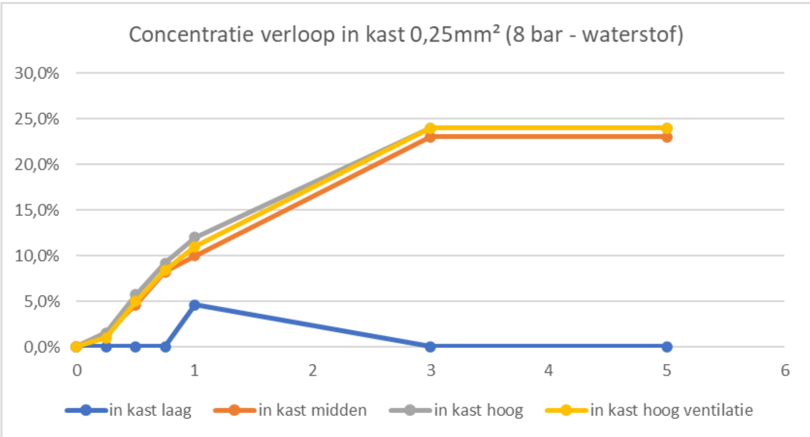


Figure 65. Concentration (vol % H_2) in the ½ m3 cabinet at a leakage rate of 5.6 m3(n)/h hydrogen

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes.

	North	East	South	West
Hydrogen concentration	21.0 vol%	21.0 vol%	18.0 vol%	22.0 vol%

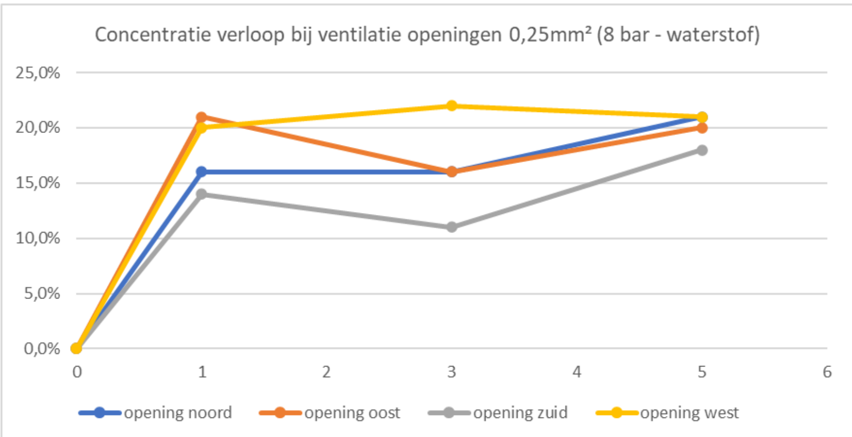


Figure 66. Concentration (vol % H_2) at the vent openings in the ½ m^3 cabinet at a leakage rate of 5.6 m3(n)/h hydrogen

During the experiment, the concentration of hydrogen outside the gas pressure regulating station occasionally rises to a maximum of 18% LEL/LFL. At a distance of 0.5 meters from the gas cabinet, hydrogen sensors at a height of 1 meter were also measured. These have a measurement range of up to 1000 ppm and this was also achieved.

Leakage rate 0.40 m^3_n /hr - natural gas (leakage opening 0.25 mm²) - 1 bar

At a leakage rate of 0.40 m^3_n /h, the natural gas concentration in the ½ m^3 gas cabinet rises to a maximum concentration of 11.9 vol%. The influence of wind was only considered if it disturbed experiments in the windless situation. No influence of wind was observed during this measurement. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

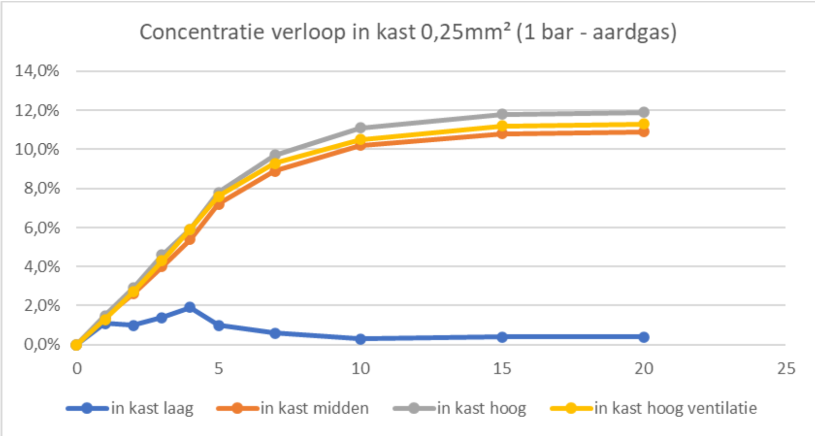


Figure 67. Concentration (vol % CH4) in the ½ m3 cabinet at a leakage rate of 0.40 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	11.3vol%	11.6vol%	4.0vol%	10.8vol%

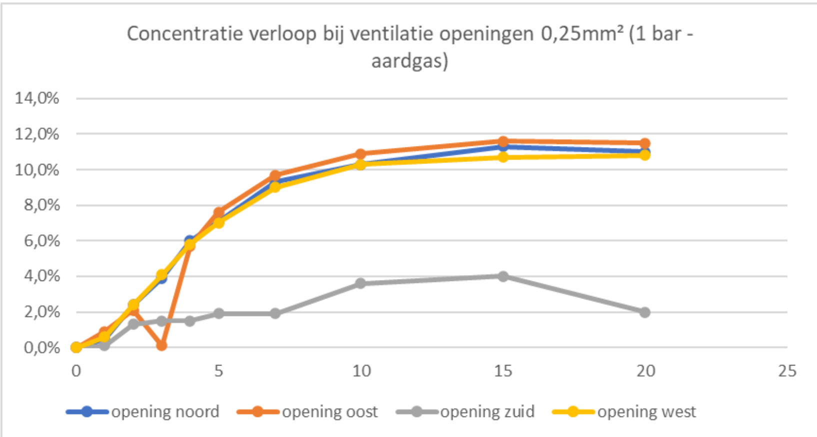


Figure 68. Concentration (vol% CH_4) at the vent openings of a ½ m3 cabinet at a leakage rate of 0.40 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 1.25 m^3_n /hr - hydrogen (leakage opening 0.25 mm²) - 1 bar

When a hydrogen leak was created with the same pressure, the measured leakage flow rate was about 1.25 m^3_n /h. This leak led to a hydrogen concentration of up to 11 vol% in the casing. The test is shorter than other tests due to the significant gas concentration that builds up in the casing in a short time. The influence of wind was only considered if it interfered with experiments in the windless situation. No influence was observed during this measurement. The graph below shows the concentration of hydrogen as a function of time in minutes (and seconds). Due to the high concentration, the experiment was stopped after a short time.

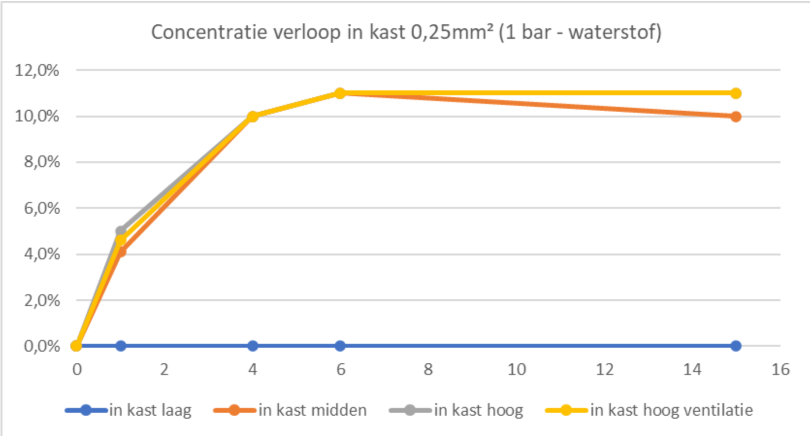


*Figure 69. Concentration (vol % H_2) in the ½ m3 cabinet at a leakage rate of 1.25 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes (and seconds).

	North	East	South	West
Hydrogen concentration	10.0 vol%	11.0 vol%	6.5 vol%	11.0 vol%

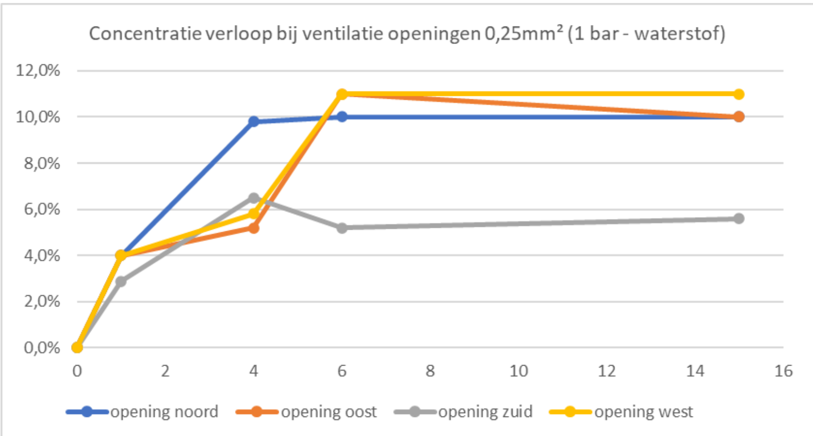


Figure 70. Concentration (vol % H_2) at the vent openings in the ½ m^3 cabinet at a leakage rate of 1.25 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and 580 ppm was achieved.

*) the sensor low in the housing recorded only zero values during this test.

Leakage rate 0.18 m^3_n /hr - natural gas (leakage opening 0.025 mm^2) - 8 bar

In the first test, the smallest leakage opening in accordance with IGEM/SR/25 Edition 2 was created at a pressure of 8 bar in the ½ m^3 gas cabinet with the concentration rising to a maximum of 6.0 vol%. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

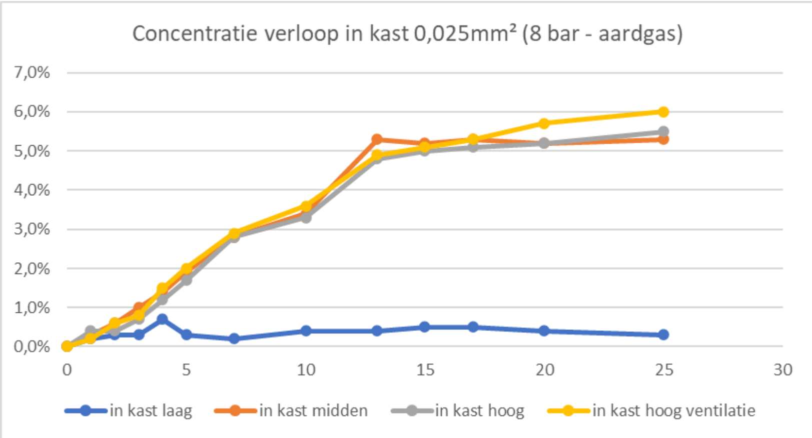


Figure 71. Concentration (vol% natural gas) in the ½ m3 cabinet at a leak of 0.025 mm² at 8 bar

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	6.0vol%	6.0vol%	2.0vol%	0.1vol%

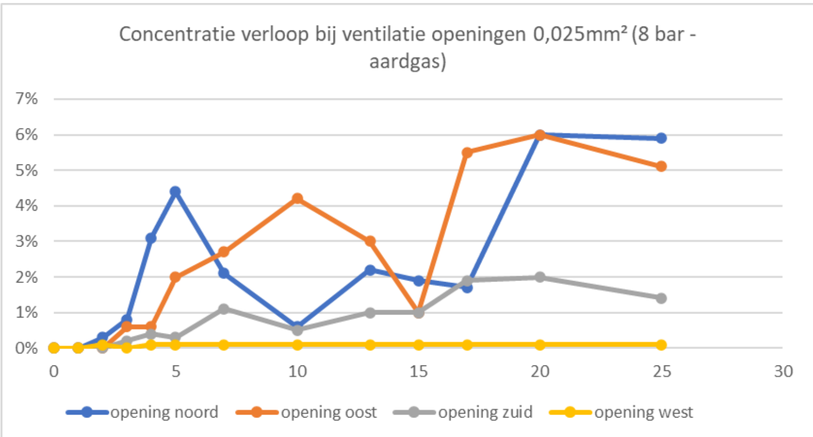


Figure 72. Concentration at the vent openings (vol% natural gas) in the ½ m³ cabinet at a leak of 0.025 mm² at 8 bar

At a distance of 0.5 meters from the housing, measurements were also made with sensors at a height of 1 meter. These have a measurement range of up to 1000 ppm and occasionally 100 ppm was reached. At a
distance of 0.5 meters, no LEL/LFL values were detected.

Leakage rate 0.56 $m^3{}_n$ /hr - hydrogen (leakage opening 0.025 mm^2) - 8 bar

When creating the defined leak with hydrogen at the same pressure, the measured leak rate was about 0.56 $m^3{}_n$ /h. This leak led to a hydrogen concentration of up to 6.9 vol% in the casing.

The concentration at all measurement points in the gas cabinet stabilises after about 10 minutes and then remains almost the same throughout the test. The graph below shows the concentration of hydrogen as a function of time in minutes.

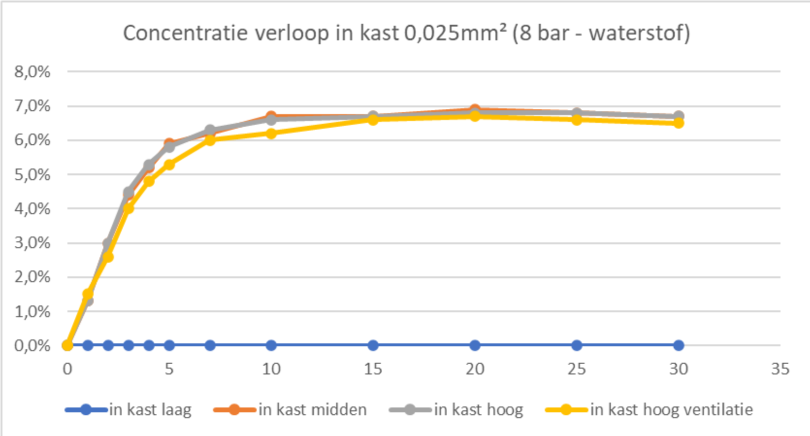


*Figure 73. Concentration (vol % H_2) in the ½ m^3 cabinet at a leakage rate of 0.56 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes.

	North	East	South	West
Hydrogen concentration	6.3vol%	6.4vol%	4.5vol%	6.4vol%

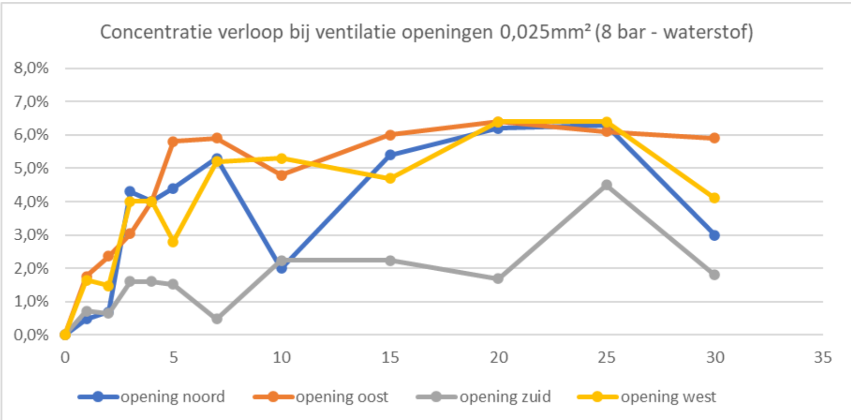


Figure 74. Concentration (vol% H2) at the vent openings in the ½ m^3 cabinet at a leakage rate 0.56 m3(n)/h hydrogen

A distance of 0.5 meters from the gas cabinet was also measured with hydrogen sensors at a height of 1 meter. These have a measurement range up to 1000 ppm and values up to 580 ppm were achieved on the west side of the gas cabinet. At a distance of 0.5 meters, no LEL/LFL values were detected.

*) the sensor low in the housing recorded only zero values during this test.

Leakage rate 0.04 m^3_n /hr - natural gas (leakage opening 0.025 mm^2) - 1 bar

At a leakage rate of 0.040 m^3_n /h, the natural gas concentration in the ½ m^3 gas cabinet rises to a maximum concentration of 1 vol%. The influence of wind was only considered if it disturbed experiments in the windless situation. During this measurement, minimal influence of wind was observed causing slight preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

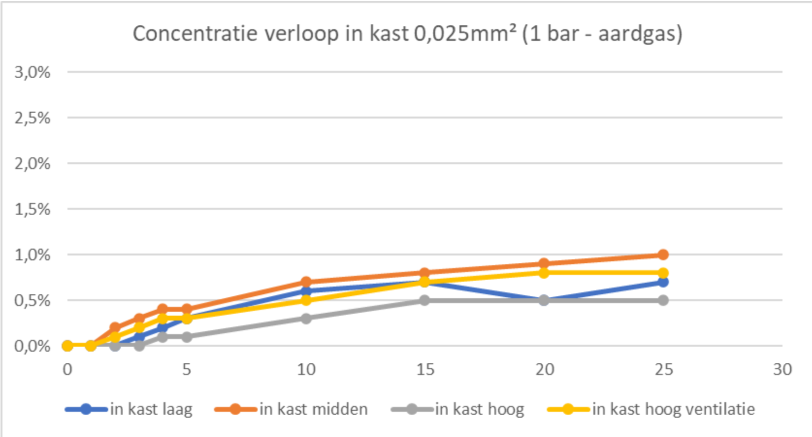


Figure 75. Concentration (vol % CH4) in the ½ m3 cabinet at a leakage rate of 0.040 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	1.0vol%	0.5vol%	0.1vol%	0.4vol%

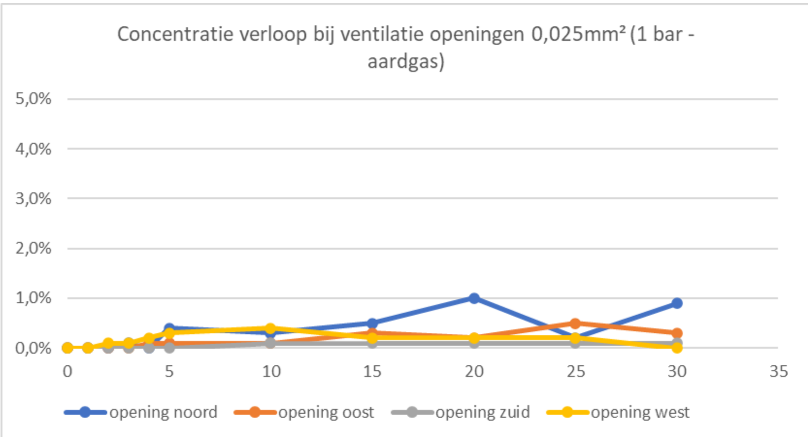


Figure 76. Concentration (vol% CH_4) at the vent openings of a ½ m3 cabinet at a leakage rate of 0.040 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 0.125 m^3_n /hr - hydrogen (leakage opening 0.025 mm^2) - 1 bar

When a hydrogen leak was created with the same pressure, the measured leakage flow rate was about 0.125 m^3_n /h. This leak led to a hydrogen concentration of up to 2.7 vol% in the casing. The influence of wind was only considered if it interfered with experiments in the windless situation. No influence was observed during this measurement. The graph below shows the hydrogen concentration as a function of time in minutes (and seconds).

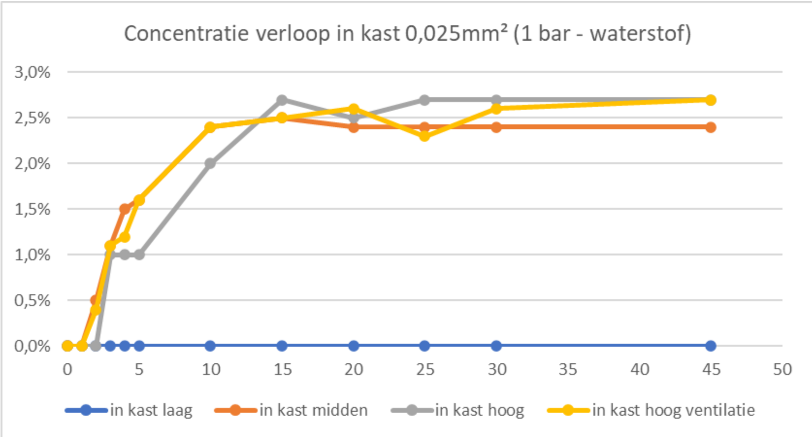


*Figure 77. Concentration (vol % H_2) in the ½ m3 cabinet at a leakage rate of 0.125 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes (and seconds).

	North	East	South	West
Hydrogen concentration	2.9 vol%	2.6 vol%	1.4 vol%	3.1 vol%

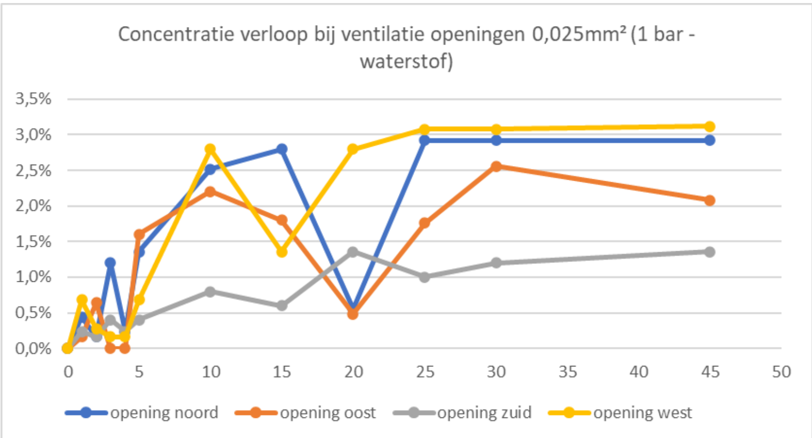


Figure 78. Concentration (vol % H_2) at the vent openings in the ½ m^3 cabinet at a leakage rate of 0.125 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and 260 ppm was achieved. At a distance of 0.5 meters, no LEL/LFL values were detected.

*) the sensor low in the housing recorded only zero values during this test.

IX Measurement results - 4 m3 cabinet station

Leakage rate 1.8 m^3_n /hr - natural gas (leakage opening 0.25 mm²) - 8 bar

At a leakage rate of 1.8 m^3_n /h, the natural gas concentration in the 4 m^3 gas cabinet rises to a maximum concentration of 4.3 vol%. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, a small influence of wind was observed causing preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

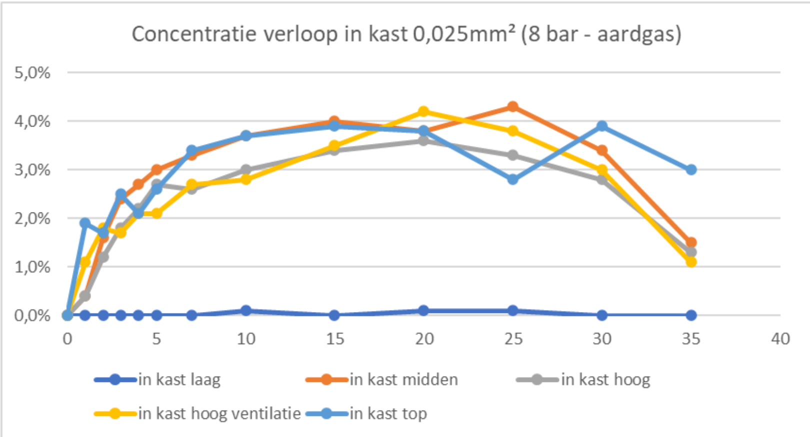


Figure 79. Concentration (vol % CH4) in the 4 m3 cabinet at a leakage rate of 1.8 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	2.6vol%	1.0vol%	3.7vol%	3.7vol%

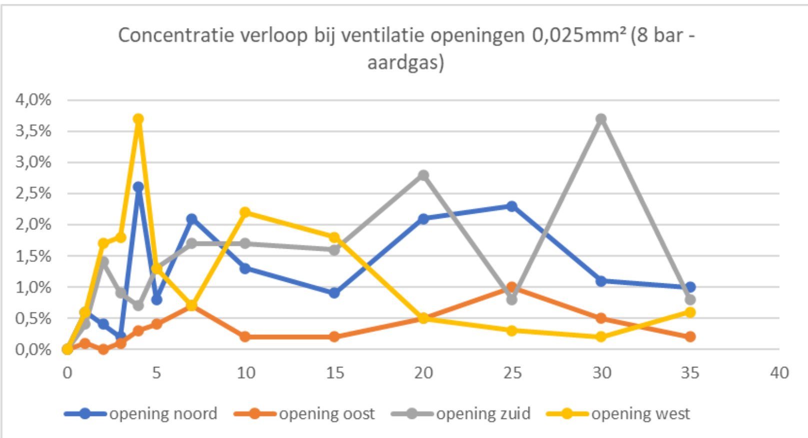


Figure 80. Concentration (vol% CH_4) at the vent openings of a 4 m3 cabinet at a leakage rate of 1.8 m3(n)/h

At a distance of 0.5 meters from the housing, measurements were also made with sensors at a height of 1 meter. These have a measurement range of up to 1000 ppm and incidentally 100 ppm was reached. At a distance of 0.5 meters, no LEL/LFL values were detected.

Leakage rate 5.6 m^3_n /hr - hydrogen (leakage opening 0.25 mm²) - 8 bar

When a hydrogen leak was created with the same pressure, the measured leakage flow rate was about 5.6 m^3_n /h. This leak led to a hydrogen concentration of up to 12 vol% in the casing. The test is shorter than other tests due to the significant gas concentration that builds up in the casing in a short time. The influence of wind was only considered when it interfered with experiments in the windless situation. During this measurement, only minor influence was observed. The graph below shows the concentration of hydrogen as a function of time in minutes (and seconds).

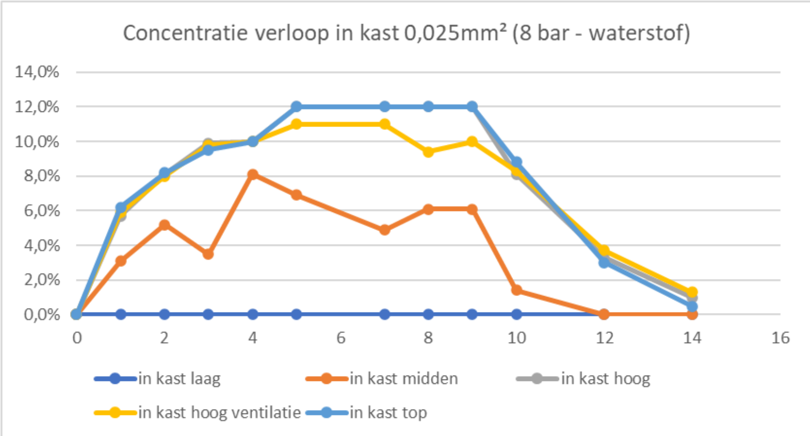


*Figure 81. Concentration (vol % H_2) in the 4 m3 cabinet at a leakage rate of 5.6 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes (and seconds).

	North	East	South	West
Hydrogen concentration	9.1 vol%	4.0 vol%	9.3 vol%	6.0 vol%

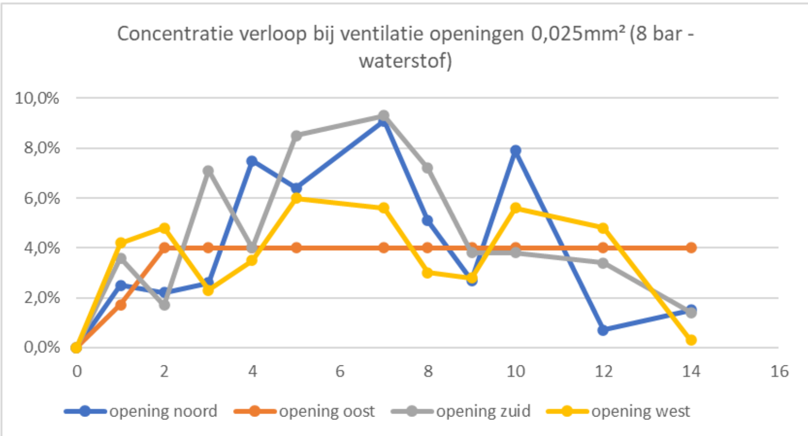


Figure 82. Concentration (vol % H_2) at the vent openings in the 4 m^3 cabinet at a leakage rate of 5.6 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and 570 ppm was achieved. At a distance of 0.5 meters, no LEL/LFL values were detected.

*) the sensor low in the housing recorded only zero values during this test.

Leakage rate 0.4 m^3_n /hr - natural gas (leakage opening 0.25 mm²) - 1 bar

At a leakage rate of 0.4 m^3_n /h, the natural gas concentration in the 4 m^3 gas cabinet rises to a maximum concentration of 3.3 vol%. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, a small influence of wind was observed causing preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

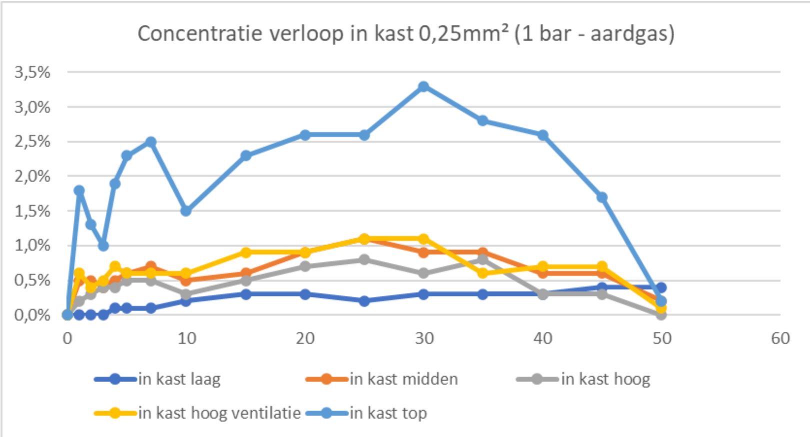


Figure 83. Concentration (vol % CH4) in the 4 m3 cabinet at a leakage rate of 0.4 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	0.9vol%	0.3vol%	0.5vol%	2.8vol%

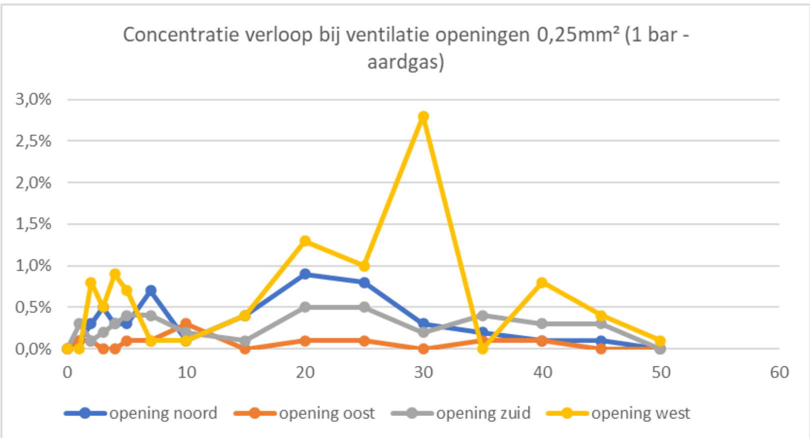


Figure 84. Concentration (vol% CH_4) at the vent openings of a 4 m3 cabinet at a leakage rate of 0.4 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 1.25 m^3_n /hr - hydrogen (leakage opening 0.25 mm²) - 1 bar

When a hydrogen leak was created with the same pressure, the measured leakage flow rate was about 1.25 m^3_n /h. This leak led to a hydrogen concentration of up to 5.5 vol% in the casing. The influence of wind was only considered when it interfered with experiments in the windless situation. During this measurement, a slight influence was observed. The graph below shows the concentration of hydrogen as a function of time in minutes (and seconds). Due to the high concentration, the experiment was stopped after a short time.

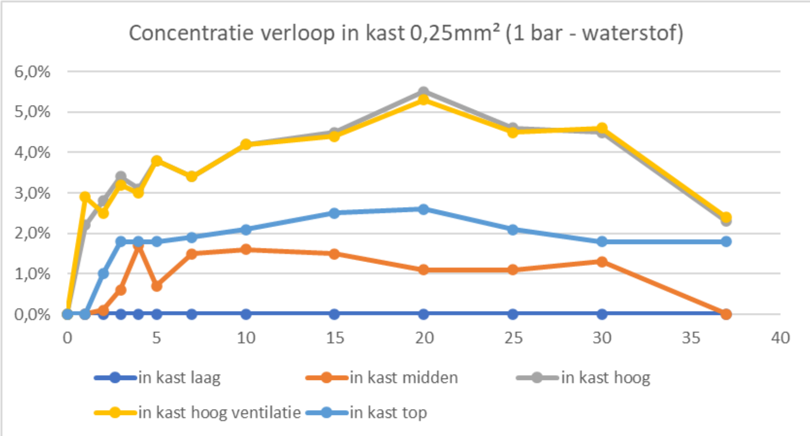


*Figure 85. Concentration (vol % H_2) in the 4 m3 cabinet at a leakage rate of 1.25 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes (and seconds).

	North	East	South	West
Hydrogen concentration	4.1 vol%	4.0 vol%	3.6 vol%	4.1 vol%

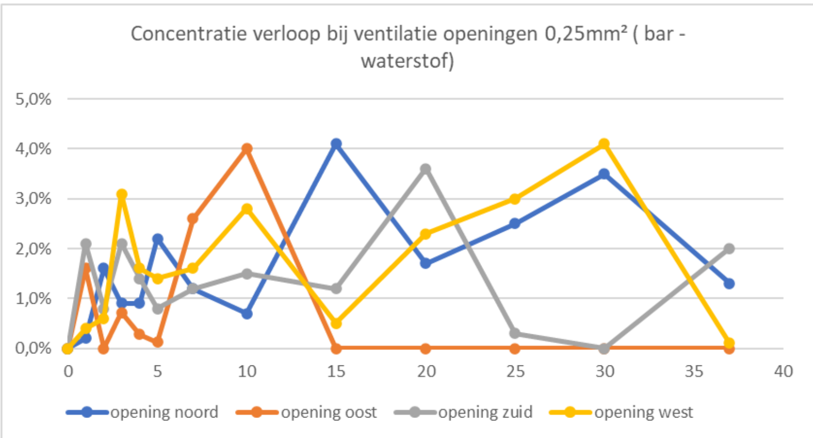


Figure 86. Concentration (vol % H_2) at the vent openings in the 4 m³ cabinet at a leakage rate of 1.25 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and 120 ppm was achieved.

*) the sensor low in the housing recorded only zero values during this test.

Leakage rate 0.18 m^3_n /hr - natural gas (leakage opening 0.025 mm²) - 8 bar

At a leakage rate of 0.18 m^3_n /h, the natural gas concentration in the 4 m^3 gas cabinet rises to a maximum concentration of 0.8 vol%. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, a small influence of wind was observed causing preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

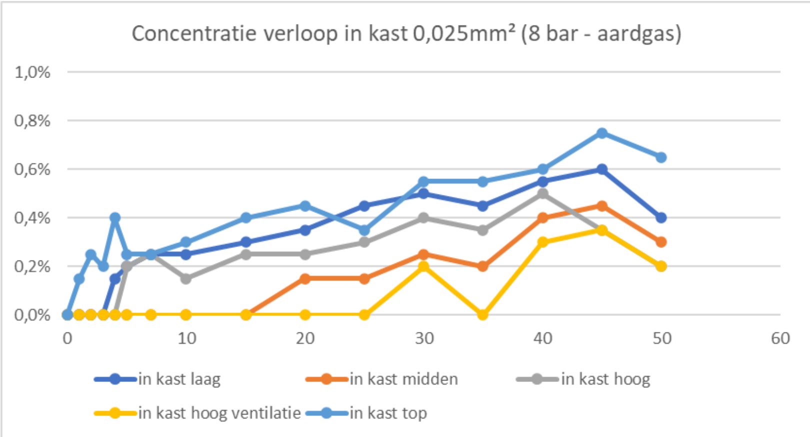


Figure 87. Concentration (vol % CH4) in the 4 m3 cabinet at a leakage rate of 0.18 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	0.2vol%	0.7vol%	0.4vol%	0.4vol%

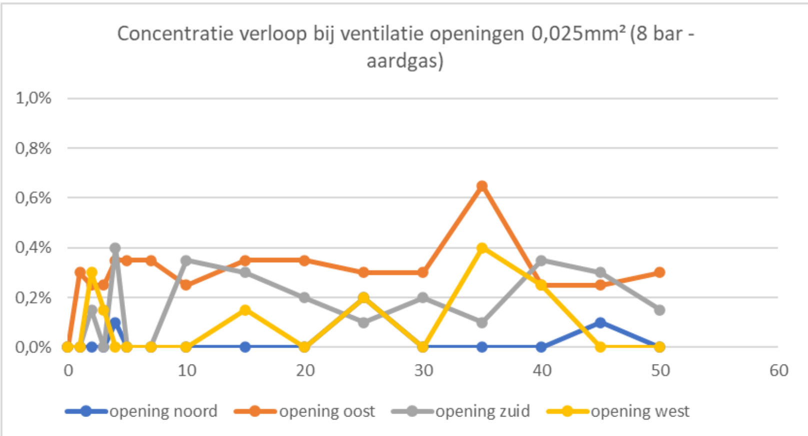


Figure 88. Concentration (vol% CH_4) at the vent openings of a 4m3 cabinet station at a leakage rate of 0.18 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 0.56 m^3_n /hr - hydrogen (leakage opening 0.025 mm²) - 8 bar

When creating the defined leak with hydrogen at the same pressure, the measured leak rate was about 0.56 m^3_n /h. This leak led to a hydrogen concentration of up to 2.6 vol% in the gas cabinet. The concentration at all measurement points in the gas cabinet stabilizes after about 10 minutes and then remains almost the same throughout the test. The graph below shows the hydrogen concentration as a function of time in minutes.

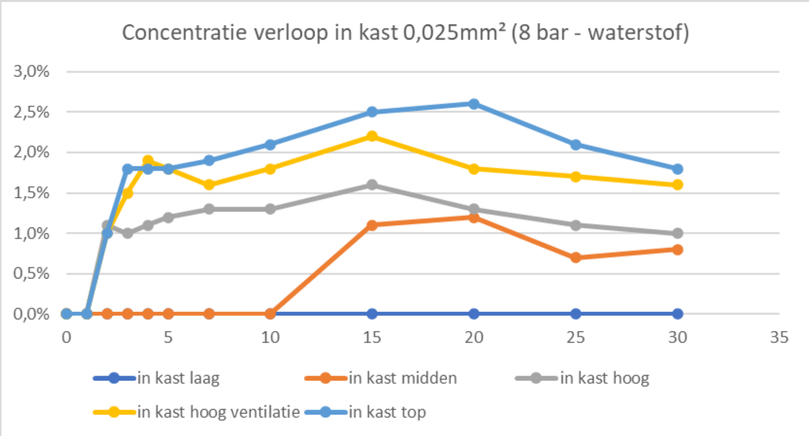


*Figure 89. Concentration (vol % H_2) in the 4 m³ cabinet at a leakage rate of 0.56 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes.

	North	East	South	West
Hydrogen concentration	0.9vol%	1.6vol%	1.1vol%	1.3vol%

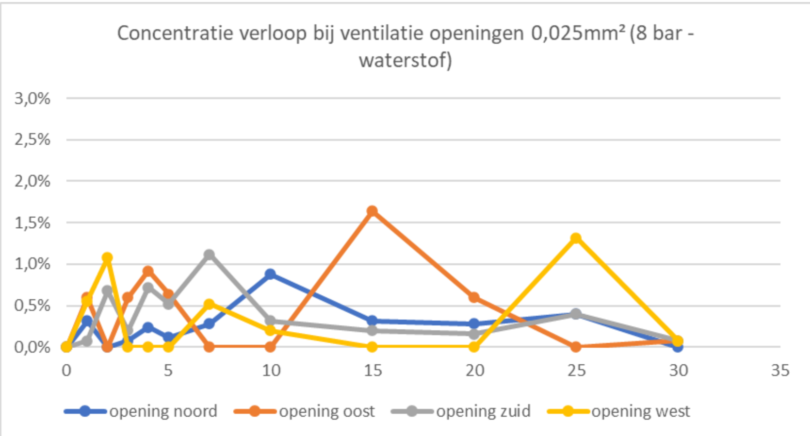


Figure 90. Concentration (vol% H2) at the vent openings in the 4 m³ cabinet at a leakage rate 0.56 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and 70 ppm was achieved. At a distance of 0.5 meters, no LEL/LFL values were detected.

*) the sensor low in the housing recorded only zero values during this test.

Leakage rate 0.04 m^3_n /hr - natural gas (leakage opening 0.025 mm^2) - 1 bar

At a leakage of 0.04 m^3_n /h, the natural gas concentration in the 4 m^3 gas cabinet rises to a maximum concentration of 0.2 vol%. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, influence of wind was observed causing preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

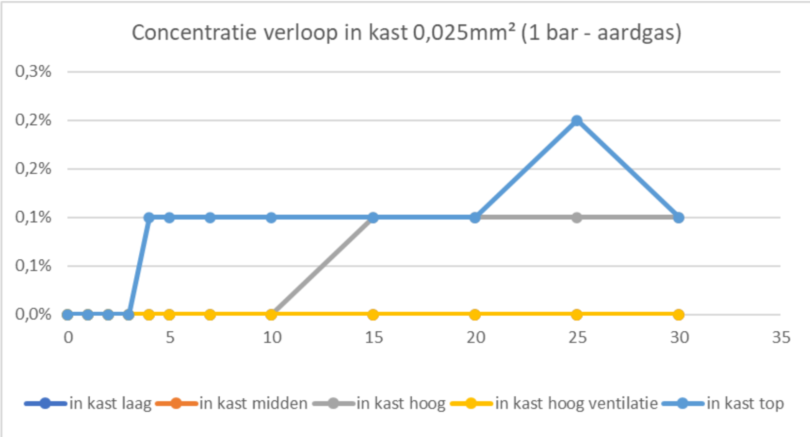


Figure 91. Concentration (vol % CH4) in the 4 m3 cabinet at a leakage rate of 0.04 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	North	East	South	West
Natural gas Concentration	0.0vol%	0.0vol%	0.0vol%	0.1vol%

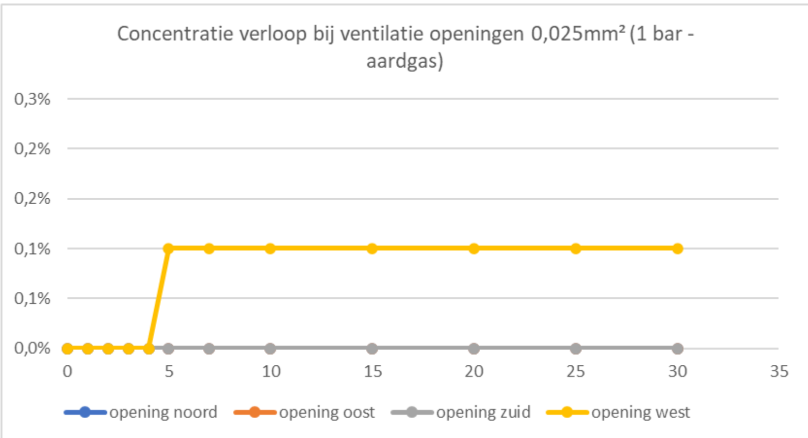


Figure 92. Concentration (vol% CH_4) at the vent openings of a 4m3 cabinet station at a leakage rate of 0.04 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 0.125 m^3_n /hr - hydrogen (leakage opening 0.025 mm²) - 1 bar

When a hydrogen leak was created with the same pressure, the measured leakage flow rate was about 0.125 m^3_n /h. This leak led to a hydrogen concentration of up to 1.0 vol% in the casing. The influence of wind was only considered if it interfered with experiments in the windless situation. No influence was observed during this measurement. The graph below shows the hydrogen concentration as a function of time in minutes (and seconds).

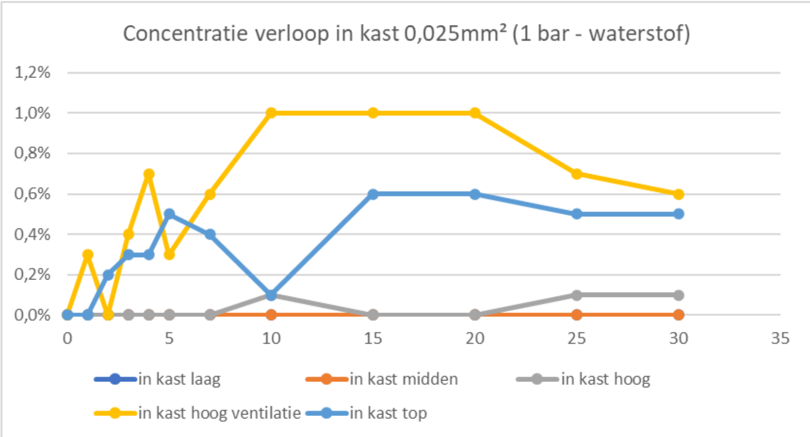


*Figure 93. Concentration (vol % H_2) in the 4 m3 cabinet at a leakage rate of 0.125 m3(n)/h hydrogen **

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes (and seconds).

	North	East	South	West
Hydrogen concentration	0.3 vol%	0.4 vol%	0.4 vol%	0.4 vol%

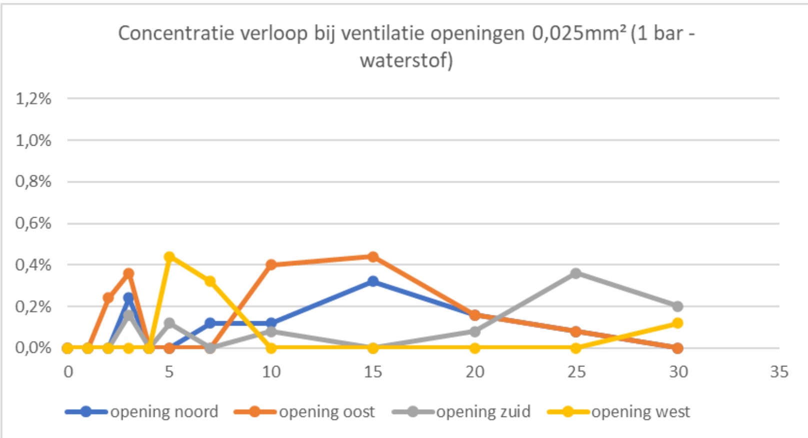


Figure 94. Concentration (vol % H_2) at the vent openings in the 4 m³ cabinet at a leakage rate of 0.125 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and only 10 ppm was achieved. At a distance of 0.5 meters, no LEL/LFL values were detected.

*) the sensor low in the housing recorded only zero values during this test.

X Measurement results - HAS cabinet

Leakage rate 0.18 m^3_n /hr - natural gas (leakage opening 0.025 mm²) - 8 bar

At a leakage of 0.18 m^3_n /h, the natural gas concentration in the HAS cabinet rises to a maximum concentration of 10.9 vol%. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, a small influence of wind was observed causing preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

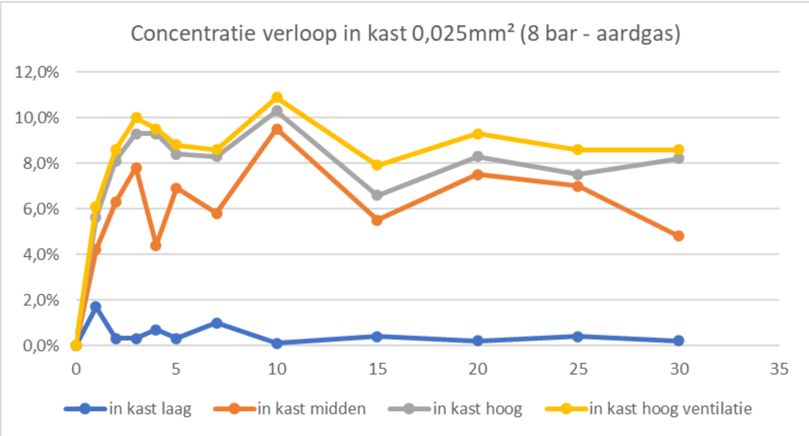


Figure 95. Concentration (vol % CH4) in the HAS cabinet at a leakage rate of 0.18 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	Left front	Right front
Natural gas Concentration	9.1vol%	7.9vol%

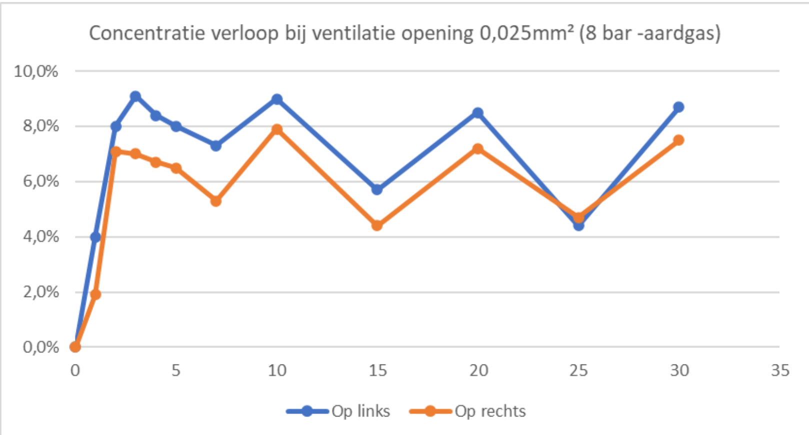


Figure 96. Concentration (vol% CH_4) at the vent openings of a HAS cabinet at a leakage rate of 0.18 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 0.56 m^3_n /hr - hydrogen (leakage opening 0.025 mm²) - 8 bar

When creating the defined leak with hydrogen at the same pressure, the measured leak rate was about 0.56 m^3_n /h. This leak led to a hydrogen concentration in the HAS cabinet of up to 12 vol%. The test is shorter than other tests due to the significant gas concentration that builds up in the gas cabinet in a short time. The influence of wind was only considered when it interfered with experiments in the windless situation. During this measurement, a slight influence was observed. The graph below shows the concentration of hydrogen as a function of time in minutes.

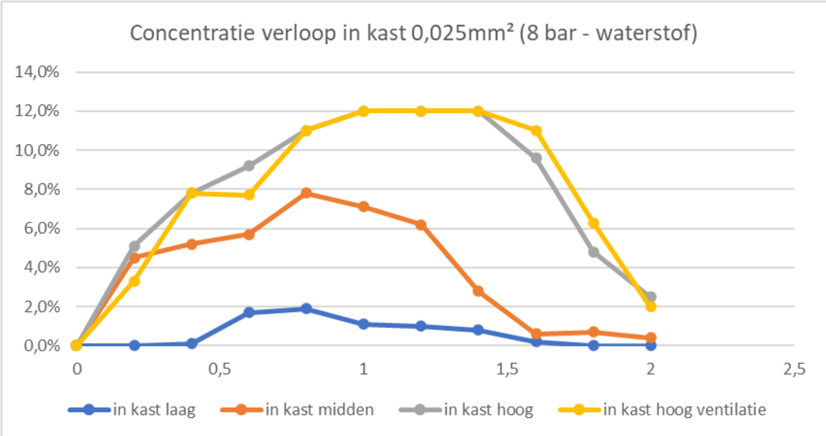


Figure 97. Concentration (vol % hydrogen) in the HAS cabinet at a leakage rate of 0.56 m3(n)/h hydrogen

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes.

	Left front	Right front
Hydrogen concentration	12.0vol%	12.0vol%

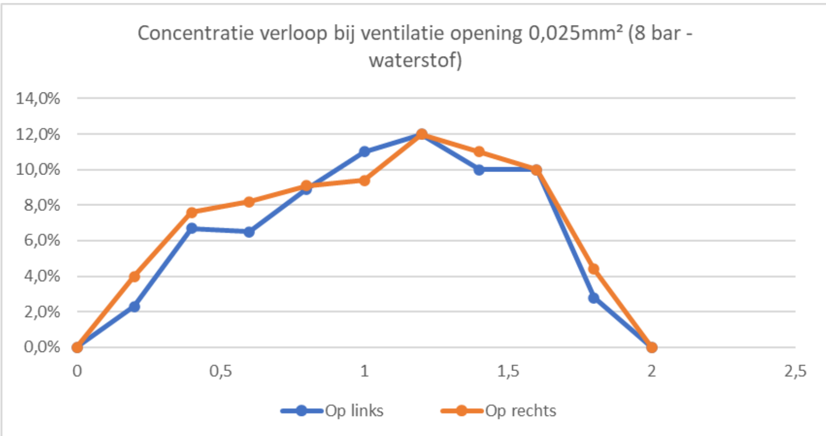


Figure 98. Concentration (vol % H2) at the vent openings in the HAS cabinet at a leakage rate of 0.56 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors were also measured at a height of 1 meter. These have a measurement range of up to 1000 ppm and 410 ppm was reached. At a distance of 0.5 meters, no LEL/LFL values were detected.

Leakage rate 0.04 m^3_n /hr - natural gas (leakage opening 0.025 mm^2) - 1 bar

At a leakage of 0.04 m^3_n /h, the natural gas concentration in the HAS cabinet rises to a maximum concentration of 3.3 vol%. The influence of wind was only considered when it disturbed experiments in the windless situation. During this measurement, a small influence of wind was observed causing preference on the vent openings. The graph below shows the concentration of natural gas (in vol%) as a function of time in minutes.

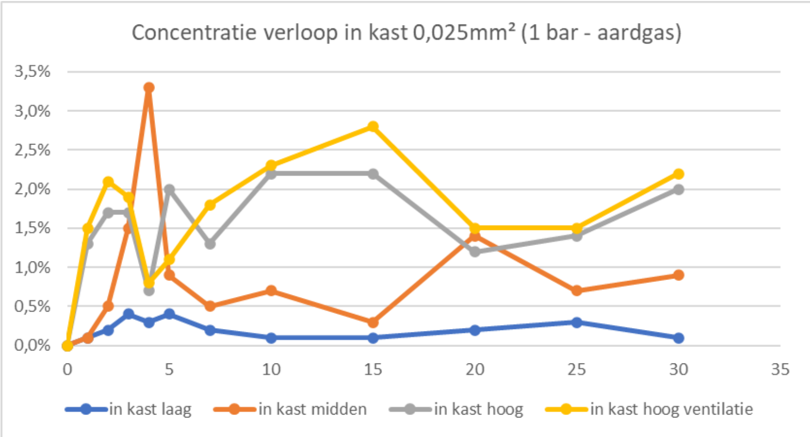


Figure 99. Concentration (vol % CH4) in the HAS cabinet at a leakage rate of 0.04 m3(n)/h

The graph and table below shows the time-dependent picture of the measured concentration of natural gas (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes.

	Left front	Right front
Natural gas Concentration	3.9vol%	2.7vol%

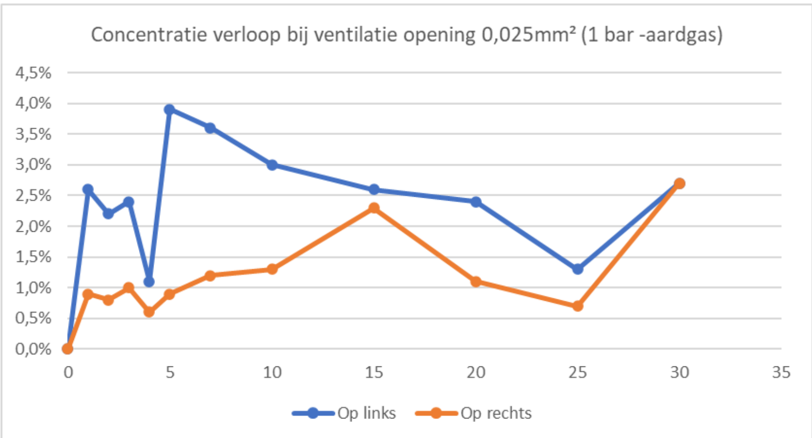


Figure 100. Concentration (vol% CH_4) at the vent openings of a HAS cabinet at a leakage rate of 0.04 m3(n)/h

At a distance of 0.5 meters from the cabinet, no natural gas concentration was measured at any time, thus remaining below 0.1% LEL/LFL.

Leakage rate 0.125 m^3_n /hr - hydrogen (leakage opening 0.025 mm^2) - 1 bar

When creating the defined leak with hydrogen at the same pressure, the measured leak rate was about 0.125 m^3_n /h. This leak led to a hydrogen concentration in the HAS cabinet of up to 5.8 vol%. The influence of wind was only considered if it interfered with experiments in the windless situation. During this measurement, a slight influence was observed. The graph below shows the concentration of hydrogen as a function of time in minutes and seconds.

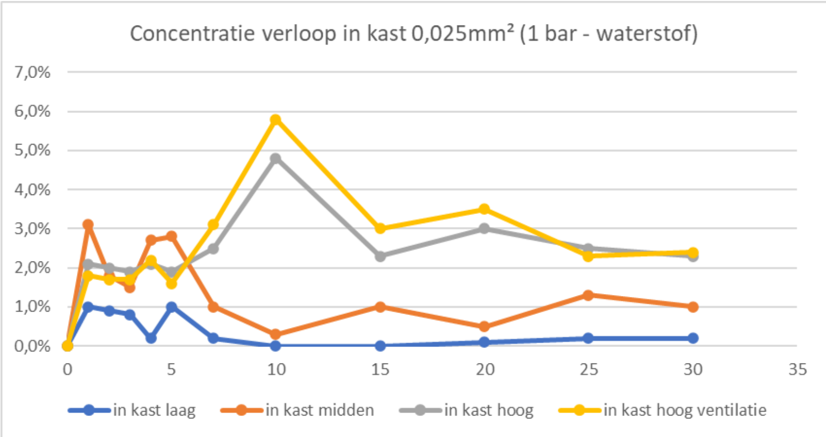


Figure 101. Concentration (vol % hydrogen) in the HAS cabinet at a leakage rate of 0.125 m3(n)/h hydrogen

The graph and table below shows the time-dependent picture of the measured concentration of hydrogen (in vol%) at the vent openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes.

	Left front	**Right front**
Hydrogen concentration	5.6vol%	4.1vol%

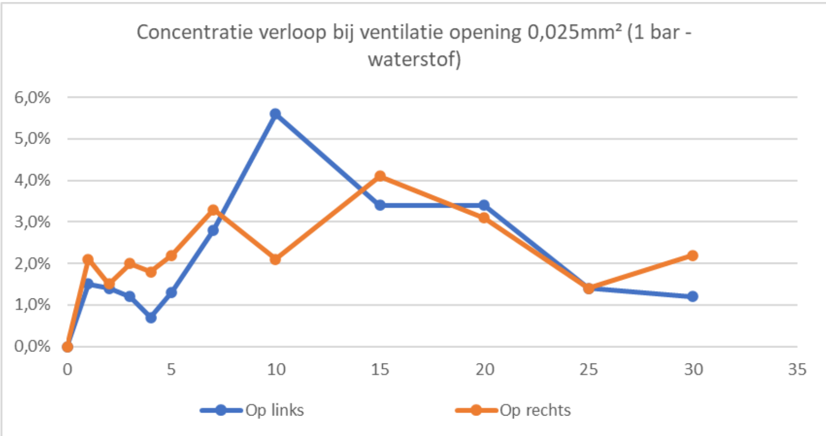


Figure 102. Concentration (vol % H2) at the vent openings in the HAS cabinet at a leakage rate of 0.125 m3(n)/h hydrogen

At a distance of 0.5 meters from the gas cabinet, hydrogen sensors at a height of 1 meter were also measured. These have a measurement range of up to 1000 ppm and only 20 ppm was achieved. At a distance of 0.5 meters, no LEL/LFL values were detected.