SICK AG WHITEPAPER

INFLUENCE OF ALTERNATIVE ENERGY CARRIERS ON TUNNEL SAFETY - H_2 MEASUREMENTS IN ROAD TUNNELS

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Unprecedented switch in fleet composition

Traditional energy carriers for road vehicles are either gasoline or diesel. To reduce emissions from transport vehicles, alternative energy carriers are expected to replace these traditional energy carriers. The number of vehicles powered with alternative energy carriers is expected to increase significantly in the next years. The composition of the vehicle fleets that use tunnels will therefore change with unprecedented speed and magnitude towards alternative energy powered drive trains and vehicles. This might impact the safety in road tunnels.

Traditional alternative energy carriers

There are two alternative fuel technologies that are already used with significant market share in certain countries.

Liquified petroleum gas

Liquified petroleum gas (LPG, also called Autogas) is composed of Propane / Butane. The gas is produced in oil refineries. LPG is liquified under pressures between 5 to 10 Bar. LPG "is [one of] the most widely used and accepted separate alternative to the conventional petroleum-based transport fuels, gasoline, and diesel. A number of countries today have well-developed Autogas markets. Global consumption of Autogas has been rising steadily in recent years, reaching 27.1 million tons in 2019. There are now over 27.8 million Autogas vehicles in use around the world. Yet Autogas use is still concentrated in a small number of countries: just a few countries – Turkey, Russia, South Korea, Poland, Ukraine, and Italy – together accounted for half of global Autogas consumption in 2019." (WLPGA, 2022)

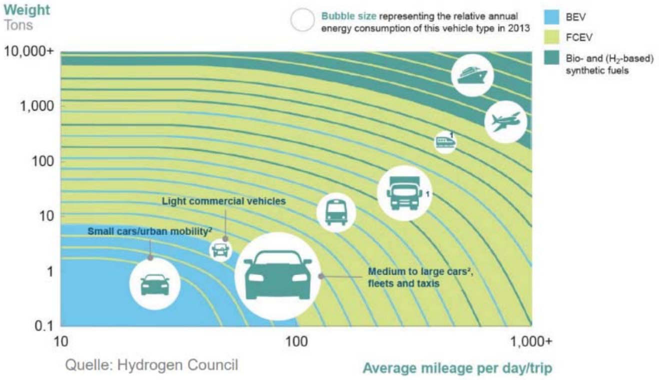
Compressed natural gas

Compressed natural gas (CNG) is mainly composed of methane. Methane is not as easily compressed as LPG. Therefore, it is stored compressed in high-pressure vessels. The use of CNG is also limited to a few countries where the top three countries are China, Iran, and India. With about 28 million vehicles equipped with CNG it is in the same range as LPG. CNG is used in a variety of land-based motor vehicles, from two wheelers through to off-road (NGVGlobal, 2022).

Both of these traditional alternative energy carriers (LPG and CNG) have been on the market for a long time. However, they have not demonstrated the potential to reach a significant share of vehicles compared to diesel or gasoline. They will remain a part of the local fleet composition where they already have a share of the market, but we do not expect that this will change over the next decade.

Future alternative energy carriers

To reach emission reduction targets, the mobility sector needs to reach the zero-emission state. Alternative energy carriers that can potentially offer zero emission mobility are Battery Electric Vehicles (BEV) where electric is stored in batteries, Fuel Cell Electric Vehicles (FCEV) where the energy is chemically stored in hydrogen and then converted in a fuel cell to electricity and bio or synthetic fuels (e.g., ammonia).
These energy carriers differ in their efficiency, the vehicle autonomy, and the charging time of the vehicle. This makes the different energy carriers a better or worse fit for different vehicle classes.



Quelle: Hydrogen Council

Battery electric vehicles

Battery electric vehicles are forecast to dominate in the car and urban transport sector due to battery energy content increases, e.g., to cover longer distances and / or higher vehicle weights, and decreases in battery weight, cost, and charging. For heavy goods vehicles and long-distance buses, the additional battery weight cannibalizes the weight of the goods that can get transported and the long charging times decrease the commercial efficiency of the vehicle. With future improvements in battery technology this disadvantage may decrease, and battery powered electric vehicles could cover more transport applications.

Fuel cell electric vehicles

Fuel cell electric vehicles use hydrogen as energy carrier. The hydrogen is converted into electric energy with the help of a fuel cell. To cover peak energy demands from the drivetrain, fuel cell electric vehicles feature a small battery that buffers electric energy (Köhler, 2009). The weight to energy relation of hydrogen as an energy carrier is much more favorable than with a battery as energy carrier. As the battery has only to cover peak energy demands its size, and weight does not increase with the distance. This improves the vehicle weight to transport weight relation. At the same time, the time to store energy in the vehicles is much shorter with hydrogen than it is with batteries. This makes fuel cell electric vehicles interesting for HGVs, long-distance buses as well as trains.

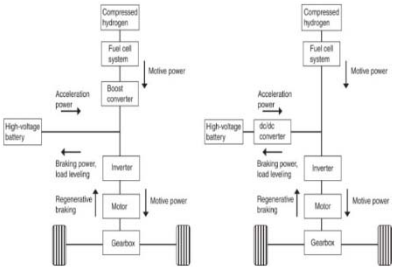


Figure 1: (Köhler, 2009)

Synthetic fuels and Ammonia

As the weight or the distance to cover by the vehicles increases, as is the case with air crafts or ships, Synthetic fuels, and ammonia have their advantage as energy carriers due to their higher ease of storage and stored energy content.

Storage technologies

“The Global Technical Regulation No. 13 (GTR #13) establishes vehicle requirements for hydrogen FCEVs that can attain equivalent levels of safety as those for conventional gasoline powered vehicles. GTR#13 is intended to be applied globally” (Austin M. Glover, 2020)

GTR #13 provides requirements for the integrity of compressed and liquid hydrogen motor vehicle fuel systems, including pressure cycling tests, a burst test, a permeation test, and a bonfire test (Austin M. Glover, 2020).

- **The pressure cycling test** evaluates a container’s durability to withstand, without burst, 22,000 cycles of pressurization and depressurization.
- **The burst test** evaluates a container’s initial strength and resistance to degradation over time.
- **The bonfire test** evaluates the ability of the container’s thermal pressure relief device to open in a fire scenario (localized and engulfing)

Compressed hydrogen storage

This is the most used storage technology for hydrogen now. The gas is stored in high-pressure vessels. These pressure vessels are classified in four different standard types due to their type of construction. Type I and II vessels are not suited for hydrogen storage in vehicles due to their weight. Useful storages are (Henrietta W. Langmi, 2021).

- **Type III** vessels comprise a fully wrapped composite cylinder with a metal liner that serves as the hydrogen permeation barrier. The metal liner is made of aluminum (Al), which solves the problem of embrittlement, and it contributes >5% to the mechanical resistance [1]. The composite overwrap (usually carbon fiber embedded in resin) acts fully as the load-bearing component. Type III vessels offer a 25%–75% mass gain over Types I and II vessels, making them more suitable for vehicle applications; however, they are more costly. Type III vessels have also been shown to be reliable at pressures up to 450 bar but there are still challenges associated with pressure cycling tests at 700 bar.
- **Type IV** vessels comprise a fully wrapped composite cylinder with a plastic liner (typically high-density polyethylene), which acts solely as the hydrogen permeation barrier. The composite overwrap serves as the load-bearing structure and is typically made up of carbon fiber or carbon/glass fiber composite in an epoxy matrix. Type IV vessels are the lightest of the pressure vessels, making them most suitable for vehicle applications, and they can endure high pressures up to 1,000 bar. However, they are the most expensive type of high-pressure vessels.

Cryogenic hydrogen storage

Another way to increase the volumetric density of hydrogen is to bring it into liquid state. The volumetric density of liquid hydrogen is even higher than compressed hydrogen. Hydrogen has a boiling point of – 253°C. To be able to store hydrogen in liquid state it needs to get cooled and maintained below this temperature. This is also a major disadvantage of this storage technology. The cooling consumes about 25% to 40% of the energy content of the hydrogen. This decreases its efficiency. In comparison to the high-pressure storage vessels, cryogenic storage vessels operate around ambient pressures. The absence of high pressures decreases the risk associated with high-pressure storage. The downside is that the tanks need to be thermally isolated, typically through vacuum insulation (Henrietta W. Langmi, 2021).

Cryo compressed hydrogen storage

This combines compressed hydrogen storage and cryogenic hydrogen storage. These measures help to further increase the safety and the volumetric storage capacity. Additionally, adding pressure resistance to the cryogenic tank it can avoid boil off gas effectively (several days without venting). The pressures are typically below 300 Bar and therefore hold lower requirements than the pressure of up to 700 Bar for compressed hydrogen (Henrietta W. Langmi, 2021).

Commercially available today are only vessels for compressed hydrogen. However, research activities are ongoing to offer cryogenic and cryo compressed hydrogen storage vessels (Böhm, 2022).

Types of vehicles and their storage technology

"When doubling the storage pressure from 35 MPa to 70 MPa [350 to 700 bar], it results only in 1.68 times increased energy density on substance level due to the isothermal properties of hydrogen. On vehicle storage system level that increase is lower (~1.25) because of the higher tank material requirements and thus there is a higher specific weight compared to 35 MPa CGH2 storage systems." (Böhm, 2022)

- **Trains:** In trains there are fewer space restrictions. Therefore, compressed hydrogen vessels with 350 bar are used. They offer the best relation between costs and storage capacity. This may change when the hydrogen vessels cannot be placed in the individual train wagons. When the vessels need to be located in the locomotive this may lead to the use of more expensive storage vessels with 700 bar pressures or future storage technologies like cryo or cryo compressed hydrogen vessels.
- **Buses:** Similar to trains, buses have fewer space restrictions. On buses the hydrogen storage vessels are typically located on the roof. There is enough space available for the use of 350 bar pressure vessels.
- **HGVs:** Heavy good vehicles are like locomotives when it comes to the storage of hydrogen. Also here, the space available on the vehicle is reduced. Additionally, the weight of the hydrogen storage competes with the weight of goods. Today HGVs use either 350 Bar or 700 Bar vessels. Mercedes Benz is investigating cryogenic vessels for hydrogen storage on trucks.
- **Cars:** For cars hydrogen competes directly with battery electric vehicles. When hydrogen is used space is very restricted, and only 700 Bar storages vessels are used.

Associated risk

Compressed gas bottles bring a risk potential on their own. In case a compressed gas bottle loses its integrity, the contained gas can transmit energy to parts of the gas bottle and accelerate these parts to very high speeds. Gas bottles can lose their integrity thanks to:

- Impact caused by an accident
- Increased temperature and consecutive pressure increase

Risk of hydrogen

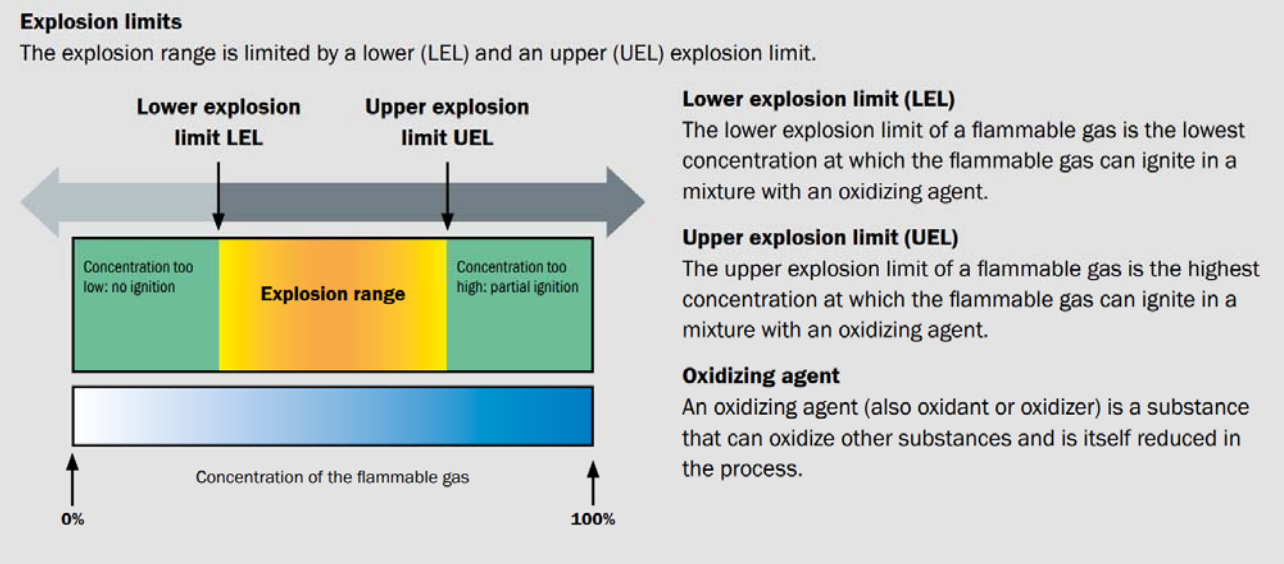
In addition to the risks associated with high pressure, hydrogen as a combustible gas adds an additional risk potential. In comparison to other energy carrying combustible gases, hydrogen has properties that increase the risk inside a tunnel (Figure 2).

- Very low minimum ignition energy
- Very wide flammability band (LEL to UEL, Figure 3)

"The largest hazards and risks in use of HFCEV in confined spaces are associated with the high-pressure on-board hydrogen storage in form of hydrogen releases, combustion, tank ruptures" (D. Makarov, 2022)

	Hydrogen	Methane	Propane	Gasoline vapor
Lower flammability limit	4%	5%	2,1%	1,2%
Upper flammability limit	75%	15%	9,5%	7,1%
Most easily ignited mixture in air	29%	8,5%	4%	2%
Buoyancy (ratio to air)	0,07	0,54	1,52	4
Minimum ignition energy	0,011 – 0.017mj	0,28-0,3mJ	0,25-0,26mJ	0.8mJ
Auto ignition temperature	500 °C	580 °C	455°c	246 – 280°C

Figure 2: Properties of hydrogen



Explosion limits

The explosion range is limited by a lower (LEL) and an upper (UEL) explosion limit.

Lower explosion limit (LEL)

The lower explosion limit of a flammable gas is the lowest concentration at which the flammable gas can ignite in a mixture with an oxidizing agent.

Upper explosion limit (UEL)

The upper explosion limit of a flammable gas is the highest concentration at which the flammable gas can ignite in a mixture with an oxidizing agent.

Oxidizing agent

An oxidizing agent (also oxidant or oxidizer) is a substance that can oxidize other substances and is itself reduced in the process.

Figure 3: G. Wallinski (2021) Measurement of combustible gases and explosive gas mixtures with cold extractive analyzers, SICK AG

Risk from heat flux

Tunnel users can be affected by the heat flux that is cause either by the combustion of hydrogen (Austin M. Glover, 2020). This risk increases with the proximity to the either a hydrogen flame or fireball / explosion (Shentsov, 2022).

Hydrogen flames are almost not visible to the human eye. They are difficult to detect for tunnel users.

Risk from overpressure

Hydrogen can combust in a diffusion flame, deflagration, or detonation.

- Hydrogen combustion with a diffusion flame where the oxidizer and fuel are separated before burning (non-premixed flame) result in minimal overpressure only.
- Hydrogen deflagration is the fast subsonic combustion of pre-mixed hydrogen and air. The ignition of the unburned gas mixture is caused by the heat in the flame front. This results in an increase of overpressure and in shock waves with speeds in the range of 1/sec.
- Hydrogen detonation is the supersonic exothermic combustion with a pressure front accelerating through a medium with speeds above 1 km/sec.

Which kind of combustion happens depends on the ratio between hydrogen and air in the gas mixture and the size of the amount or volume of the mixed gas.

In a tunnel blowdown test with a reduced size tunnel model, shock speeds between 18 m/s and 440 m/s were observed (Rattigan, 2022).

Risk in function of the tunnel length

In the open, field the risk of overpressure from shockwaves declines relatively rapidly (Austin M. Glover, 2020). Simulation of a tank rupture of a passenger car also shows a significant decay. Simulations performed for single, double, and five lane tunnels showed a faster decay in tunnels with larger cross sections. The fatality zone was restricted to the vicinity of the detonated tank, while the injury zone extended to several hundred meters. The no-harm area was never reached (Shentov, 2022). Because of the higher number of tunnel operating entities affected the risk load of long tunnels is therefore considerably higher than in short tunnels.

Pressure increase in storage vessels and integrity loss of pressure vessels

Temperature activated pressure relief devices

Fire around compressed hydrogen bottles can increase the internal pressure hydrogen vessels as described above. More severe however is that the fire weakens the structural strength of the vessels. In a worst-case scenario, this leads the loss of integrity and a sudden release of hydrogen. As a large quantity of hydrogen gets mixed with the surrounding air very rapidly, the potential for a detonation is high.

Temperature activated pressure relief devices (TPRD) release the pressurized hydrogen through an orifice in a controlled way. In the best case the hydrogen that is released through the TPRD ignites and combusts the hydrogen in a controlled diffusion flame (jet flames). The TPRD has to relieve the pressure of the hydrogen vessel before it loses its integrity. The larger the orifice, the more hydrogen gets mixed with the surrounding air in a certain amount of time. Larger orifices increase the risk of building explosive gas mixtures. The combination of durable vessels with small orifices reduces or even avoids the building of gas mixtures that can lead to deflagrations or even detonations (D. Makarov, 2022).

Intrinsically safe pressure vessel design

Alternatively, TPRD fewer tanks exclude the risk of tank rupture and its consequences – blast wave, fireball, projectiles, etc. In these tanks the inner lining that seals the tank against the compressed hydrogen loses its integrity before the tank losses its integrity. As a result, hydrogen diffuses through the carbon fiber layers of the pressure vessel (D. Makarov, 2022). This even avoids the risk of jet flames typically associated with TPRDs.

Time of ignition

The scenarios and their potential risk differ with the time of ignition. Immediate ignition scenarios result in jet fires with rather low potential risk to the tunnel users. This is different with delayed ignition. In this case, the risk arising from deflagration or detonation for the tunnel users depends on the size and mixture of the vapor cloud (Yongliang Xie, 21) (P. Russo, 2022).

H_2 measurements in road tunnels

Measurements of hydrogen can give the tunnel operators and the rescue teams useful information on the situation in the tunnel. They will detect not combusted hydrogen and indicate its location.

Explosion triangle

The Physikalische-Technische Bundesanstalt (national metrology institute of Germany) describes the formation of an explosion as follows: “For an explosion to occur, the three components “combustible substance in finely divided form [which is always the case for gases]”, oxygen and an ignition source must come together. These components can be represented as a so called “explosion triangle [Reference missing] (see Figure 4). Only if the three parts are present at the same time can an explosion happen.
A common strategy to avoid explosions is to eliminate one of the three ingredients for an explosion. As people travel in road tunnels and they require oxygen for breathing it is not possible to reduce or eliminate oxygen. In the same way it is not possible to eliminate the combustible substance or fuel as this is the alternative energy source (hydrogen) the vehicles use. The only ingredient that we might eliminate is the ignition source.

It is common practice to use gas sensors to measure the concentration of explosive gases to help to avoid explosions by eliminating ignition sources. The gas sensors measure the gas concentration as % of the lower explosion level (see Figure 3 above). As long as the combustible gas concentration is far away from the LEL there is no risk for an explosion. When the gas sensor detects that the combustible gas concentration gets closer to the LEL e.g. 50% of the LEL a control system eliminates potential ignition sources. The control system can for instance shut the electrical power in the area around the gas sensor off.

Figure 4: explosion triangle

This can be a viable way to eliminate the risk of explosion in road tunnels as well. In case hydrogen accumulates in a tunnel section, hydrogen sensors can detect the distance to the LEL and in case the concentration approximates a certain LEL threshold the tunnel control system can switch off the power in the close vicinity of the gas sensor.

Increase ventilation

Ventilation has an important effect on the hydrogen gas concentration. It helps to dilute the hydrogen. To increase the ventilation upon the detection of hydrogen is a reasonable reaction. The disadvantage of this reaction strategy is that a huge mass of air needs to be displaced by the ventilation system. This requires time in the minutes range. In this context it is discussed to analyze the incoming traffic and to increase the ventilation as soon as an FCEV approximates a tunnel. This, however, is only reasonable as long as there are only very few hydrogen-powered vehicles on the streets.

Initiate water spray

Mist dominated water sprays have a reducing effect on the temperatures in the reacting zone and the exhaust gas of H2 jet fires. The higher the mist charging rate the higher the cooling effect (Grune, 2022). It is not possible to extinguish H2 jet-fires but this would also only increase the risk of a delayed ignition of a vapor cloud. Droplet based water sprays may even depress the buoyancy effect of hydrogen (Grune, 2022). This could lead to a negative effect on the build-up of a dangerous gas cloud. To initiate a water spray system in case of hydrogen detection has to be discussed further.

Requirements of the measurements

Sensor must not be an ignition source

If the reaction upon the detection of hydrogen in the tunnel could be to power down affected tunnel sections also the hydrogen sensors must not act as ignition source. As the minimum ignition energy of hydrogen is very low, this is a demanding construction detail.

Sensor location

The buoyancy of hydrogen to air is very low. Hydrogen will travel upwards to the ceiling of the tunnel. This will be a preferred location for the placement of hydrogen sensors.

Response time sensor

As soon as hydrogen is detected and its concentration approaches LEL levels the risk in the tunnel increases very fast. The response time of the hydrogen sensors therefore need to be as fast as possible in the one-digit seconds range. This can be achieved by several sensor designs (Hübert T., 2017).

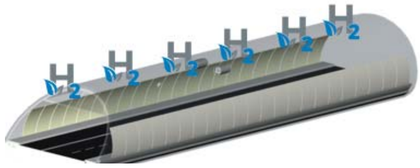


Figure 5: sensor location and high resolution

Response time – spacing / required measurement resolution

For smoke detection the requirement is typically that you detect a smoke event within 60s. This includes the reaction time of the sensor plus the travel time of the smoke to get to the sensors. The Swiss ASTRA 13004, for instance, requires that a smoke event has to be detected within 60s with an air velocity of 1,5m/s. This means that the smoke travels 90 meters in 60 seconds. This is the reason why this standard requires a smoke sensor spacing of 100m.

Applying this logic of travel time of a hydrogen gas cloud 60 seconds is way too much. A possible reaction upon the associated risk would be to slow. Hydrogen sensing would require a much higher resolution or a much lower distance between the sensors. A 10-meter spacing would bring a gas cloud travel time of about 6,5 seconds.

Special requirements for sensors used in tunnels

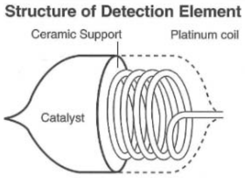
Sensors that are used in road tunnels need on one hand be able to work under the severe ambient conditions like dirt, corrosive atmosphere, humidity etc. on the other hand they need to be long term stable, and low in maintenance. A typical requirement of sensors used in tunnels is a service interval of once per year.

Available sensor technology

Hydrogen measurements are not new to the gas sensing industry. There are lots of alternative sensor designs for hydrogen measurements available. Some generic available sensor types are:

Catalytic combustion sensors

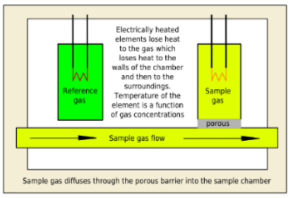
A catalytic combustion sensor (CAT) that evaluates the heat of hydrogen combustion.
The sensor consists of a detector cell and a reference cell. The detector cell basically is a platinum wire coil to which the carrier is attached, and it is coated with an oxidization catalyst such as alumina. When the powered sensor is exposed to combustible gas, the gas will burn. The reference cell is essentially an identical platinum coil, that has been treated to prevent combustible gas from igniting upon contact. (Since both cells become extremely hot during use which could ignite the combustible gas, they are enclosed in an explosion-proofed protective sintered metal and stainless steel 200-mesh netting to prevent sparking). (Gastec, 2022)



The sensitivity of a contact combustion type sensor shows almost equal sensitivity to all concentrations below the LEL (lower explosion limit) threshold of virtually all combustible gases (or mixed concentrations thereof). Therefore, almost all combustible gases can be measured with any measuring device that can be calibrated with a scale having the LEL as 100% (Gastec, 2022). Catalytic combustion sensors are therefore not selective to hydrogen.

Thermal conductivity sensors

Thermal conductivity detector (TCD) are also known as Katharometers. The increase in hydrogen concentration causes an increase of the thermal conductivity in a gas mixture and enlarges therefore the heat transfer from a sensing element to the surrounding atmosphere (Hübert T., 2017).They can be used to measure gas concentrations in a binary or quasi-binary gas mixture (Globalspec, 2022). For H2 measurements in road tunnel this means air and air + H2. The advantage is that H2 has a significantly different thermal conductivity than normal air. when the gases within the sample have distinctly different thermal conductivity values.



Semiconductor sensor

Their sensing principle relies on the change of the surface conductance due to the absorption of hydrogen onto a metal oxide semiconductor heated thick film on a ceramic substrate (Hübert T., 2017). Semiconductor metal oxides (MOXs) gained considerable attentions due to their low cost, high and fast response with relatively simplicity of use; and ability to detect a large number of gases. There are two types of MOXs namely n-type MOXs (zinc oxide, tin dioxide, titanium dioxide or iron (III) oxide responding to reducing gases (H2, CH4, CO, C2H2, and H2S); p-type MOXs (nickel oxide, cobalt oxide responding to oxidizing gases (O2, NO2, and Cl2). For the task of measuring H2 in road tunnels n-type MOX sensors could be used.

Metal isolator semiconductor

Metal-insulator-semiconductor (MIS-FET) can exploit the change of work function caused by the hydrogen absorption on a palladium, platinum or iridium gates thin film in combination with dielectric films of SiO2, Si3N4-SiO2, TiO2-SiO2, Ta2O5-SiO2, and others (Hübert T., 2017) (Boris Podlepetsky, 2018).

Other ways to measure hydrogen include laser based optical measurements (NEOMonitors, 2022) based other molecular properties (Nevadanano, 2022).

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