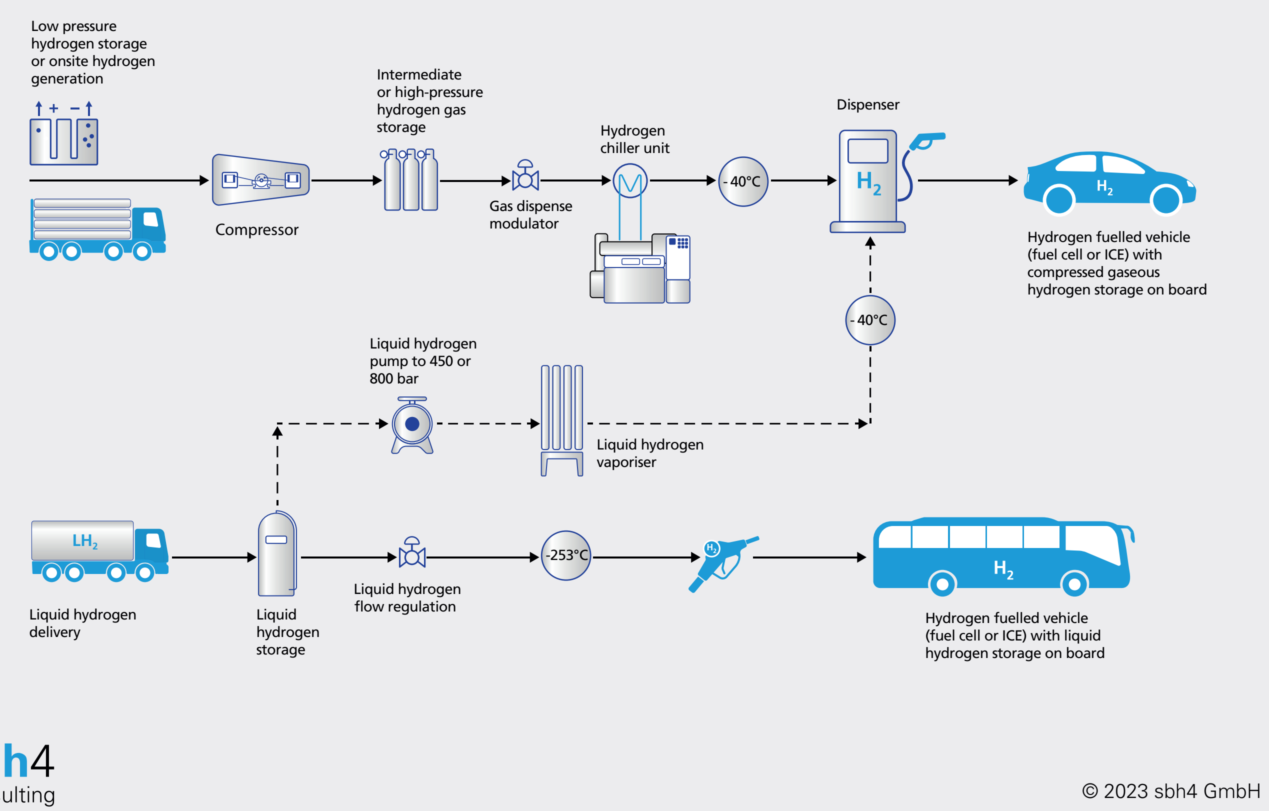
Compressed Gas, Liquid Hydrogen and Multi-Modal Hydrogen Refuelling Station Layouts



Hydrogen gas cooling equipment for refuelling stations

Why do some gases get hot and others get cold as their pressure is reduced? And why does the same gas get cold when expanding within a certain pressure range but get hot when expanding over a different pressure range? The answers lie in the Joule-Thomson effect. This thermodynamic principle can be used to liquefy natural gas to make LNG for storage and transportation. The Joule-Thomson effect is the science behind the need to cool compressed gaseous hydrogen prior to it being filled into the storage tank for hydrogen mobility applications in shipping, aviation and on land.

By Stephen B. Harrison, sbh4 consulting

Gas cylinders for hydrogen mobility

Storage of hydrogen as a compressed gas is essential for hydrogen mobility applications and the distribution of hydrogen on the roads. Robust gas cylinders are required to safely contain the hydrogen.

When designing a passenger car, space is at a premium, and a good driving range is also expected. Therefore, high-pressure storage of hydrogen is required, and the standard pressure onboard for a full tank is 700 bar.

Hydrogen gas distribution in bulk also requires a large quantity of hydrogen to be stored on the trailer. If more hydrogen can be transported in one journey, then fewer journeys, vehicles, and drivers are required. Therefore, high-pressure hydrogen storage favours economical compressed hydrogen distribution operations.

The highest-pressure storage in current operation is offered by Type 4 carbon-fibre composite cylinders. However, this is also the most expensive type of storage tank in common use.

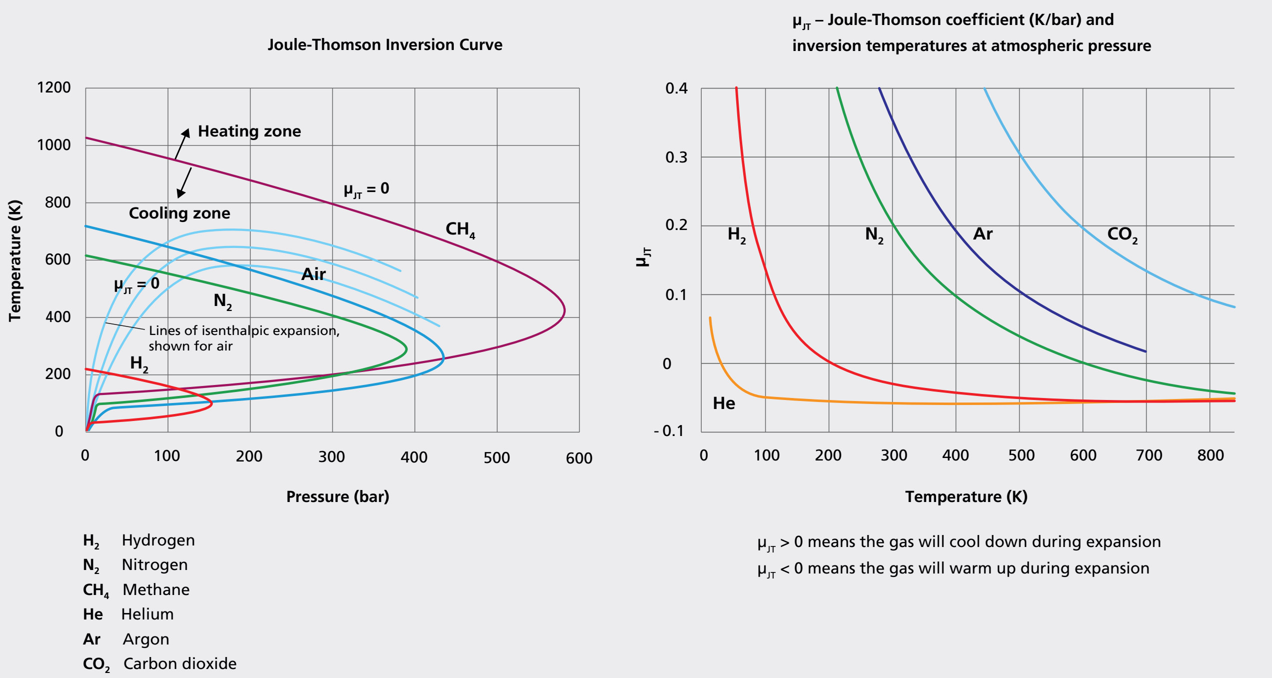
Hydrogen storage tanks on cars, trains, and trucks should not overheat during refuelling. High temperatures can overpressurise the tank or cause damage to sensitive materials. Pre-cooling the hydrogen gas is therefore safety critical.

Science is behind the need for hydrogen gas cooling

When ammonia as a refrigerant gas expands from 14 bar to atmospheric pressure, it cools to around -33°C. This principle is used to cool carbon dioxide (CO_2) and liquefy it for distribution and storage. Similarly, when propane acting as a refrigerant gas is expanded from 10 to 1 bar, it cools from 30°C to -30°C.

In the above cases, the temperature and pressure range in which the gases are expanding means that they become cold as the pressure reduces. This is because the Joule-Thomson coefficient of these gases under these conditions is greater than zero. However, under different conditions of temperature or pressure, the Joule-Thomson coefficient could be less than zero, meaning the gases would increase their temperature as they expand.

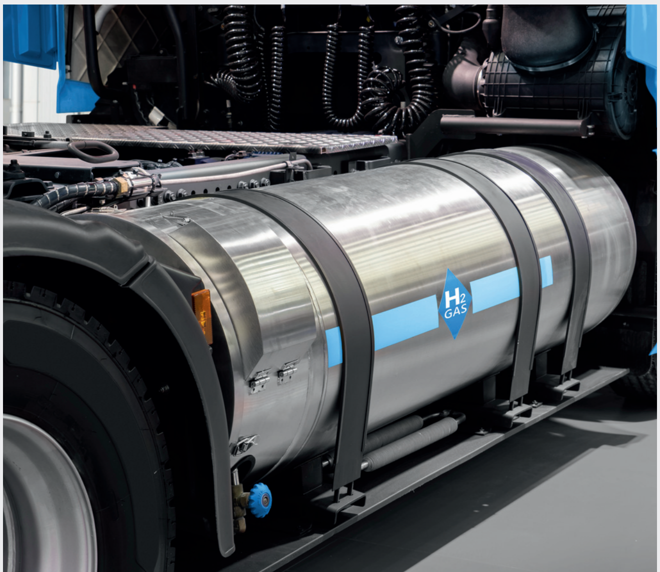
Joule-Thomson Effect for Heating and Cooling of Gases as They Expand



Compressed hydrogen gas is stored in the static intermediate pressure storage tanks at a hydrogen refuelling station (HRS) for buses or trucks at around 500 bar. For cars, the high-pressure storage at the HRS may be at around 900 bar. When the vehicle is connected to the HRS, hydrogen gas flows through the refuelling hose and nozzle from the high-pressure storage into the vehicle tank, which is at a lower pressure. Under these conditions, hydrogen gas has a Joule-Thomson coefficient less than zero and the temperature of the hydrogen gas increases.

The hydrogen storage tank on the vehicle is designed to operate at less than 85°C and has safety devices that release hydrogen when the storage tank becomes overheated. It is common to use a glass bulb thermal pressure relief device (TPRD), which bursts at 110°C. If the TPRD is activated and the glass bulb breaks, the contents of the hydrogen tank are rapidly vented.

In recognition of the growing demand for onboard hydrogen storage systems, the German high-pressure systems and equipment supplier, POPPE+POTTHOFF, has recently introduced a TPRD for hydrogen



Cryogenic liquid hydrogen storage on a truck

°LAUDA HRS cooler. Image © Lauda Dr. R. Wobser GmbH & Co. KG

storage tanks into their range of gas control equipment.

To prevent the storage tank from becoming damaged or the relief devices being deployed, the hydrogen gas must be chilled between the high-pressure storage at the HRS and the vehicle. For this purpose, a hydrogen gas cooler must be included as an element of the HRS gas dispense equipment.

Indirect coolers with thermal energy storage

Hydrogen leaving the compressor or storage tank can be as warm as 60°C. From this temperature, it must be cooled to -10, -20, -30, or -40°C, according to the relevant protocol in the SAE J2601 standard. Hydrogen gas cooling equipment manufactured by °LAUDA is designed to cool hydrogen with a temperature delta of around 100°C, from 60°C to -40°C.

Types of compressed hydrogen gas cylinder

The construction of compressed gas cylinders is categorised as Type 1, 2, 3, 4 or 5. The most common type of industrial gas cylinder is a Type 1 cylinder. It is of an all-metal construction, essentially meaning that it is made from an alloy of either steel or aluminium. The typical working pressure of such cylinders is in the range of 200 to 300 bar.

Type 1 cylinders are manufactured from metal. Type 1 steel cylinders filled to a pressure of around 300 bar are used for intermediate-pressure hydrogen storage at refuelling stations.

A **Type 2 cylinder** builds on the Type 1 construction and adds a hoop-wrap of a composite material around the metal cylinder. A hoop wrap, also referred to as a body wrap, covers the vertical wall of the cylinder but does not enclose the heel nor the shoulder. Type 2 cylinders filled to a pressure of around 1,000 bar are used for high-pressure hydrogen storage at refuelling stations.

Type 3 cylinders are similar to Type 2, but the composite wrap covers the entire metal cylinder. Type 3 cylinders are generally constructed with an aluminium alloy body with a glass fibre, Kevlar®, or carbon fibre composite wrap. When using an aluminium alloy liner and carbon fibre composite full-body wrap, the operating pressure of a Type 3 cylinder is generally 350 or 700 bar – the standard pressures for onboard hydrogen storage on trucks and buses or passenger cars.

Type 4 cylinders are of a similar construction to the Type 3 design. However, the liner is plastic, not metal. Generally, a thermosetting carbon fibre composite material is used as the wrap. The liner is generally made from polyethylene or polyamide. Where carbon fibre composite is used, the working pressure of a Type 4 cylinder can be up to 1,000 bar for static storage of compressed hydrogen gas or 700 bar where the cylinder is used to store hydrogen on a vehicle. A disadvantage of many established Type 4 hydrogen gas cylinders is that the liner is a thermoplastic material, and the wrap is a thermosetting polymer. The adhesion between the two is not perfect, and a residual pressure of around 20 bar is required in the cylinder to avoid the liner from collapsing and separating from the outer composite layer.

Type 5 cylinders are of a composite construction, without an internal liner. They have only rarely been used for aerospace and defence applications. A potential advantage of a Type 5 cylinder is that the issues of the liner separating from the outer composite layer can be avoided. This would allow the full content of the cylinder to be used, which makes storage more efficient. It would also potentially allow a vacuum to be pulled on the cylinder to enable rigorous cleaning to maintain the best possible purity of hydrogen.

°LAUDA Integral XT coolers. Image © Lauda Dr. R. Wobser GmbH & Co. KG

°LAUDA is a family-owned business with headquarters and manufacturing in Germany. They are a global leader in indirect hydrogen cooling systems. These systems use an intermediate heat transfer fluid to transfer the cold from the cooler to the dispenser. °LAUDA's indirect cooler can be located away from hydrogen gas and the dispenser in a non-ATEX zone, leaving more space around the dispenser for vehicle movements. Furthermore, cold energy can be stored in the heat transfer fluid to smooth out the cooling requirements during refuelling.

The cooling requirement at the early stages of filling is significantly greater than during the later stages. There is also a time interval between filling vehicles as they drive away from and approach the dispenser. This means that the cooling requirement is highly variable. The use of an indirect cooler with integrated thermal energy storage allows the cooler to operate at the average cooling requirement, not the peak. The equipment is therefore more compact and less expensive. The maximum power draw is also minimised.

Since 2015, °LAUDA has supplied more than 60 SUK indirect hydrogen cooling systems. °LAUDA

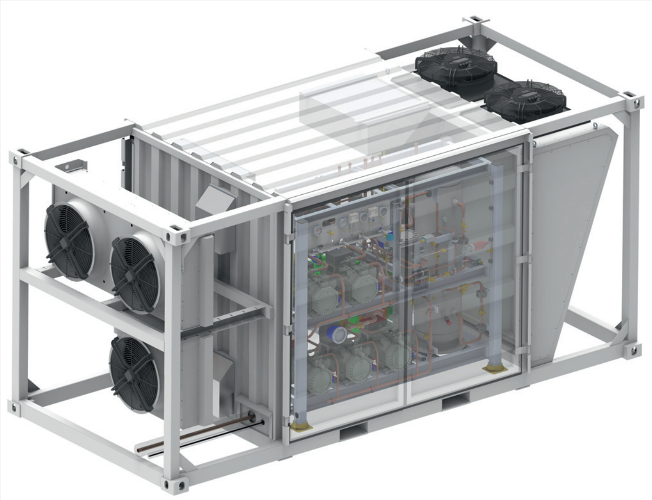
James Joule and William Thomson (Lord Kelvin)

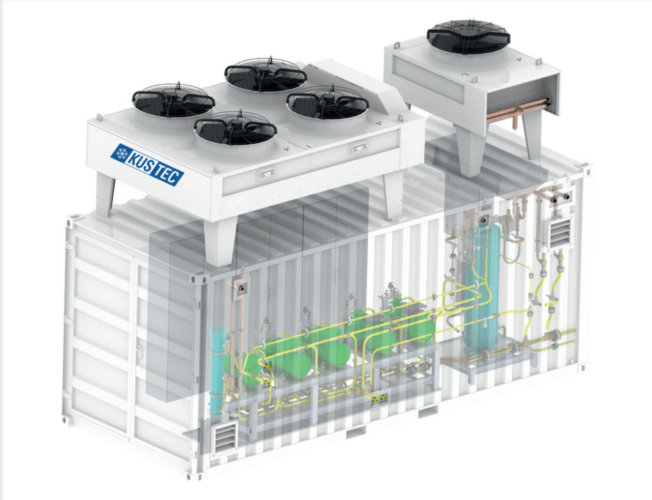
William Thomson was born in Belfast in 1824 but worked for most of his life as a professor at the University of Glasgow. In 1892, he was the first British scientist to be given a seat in the House of Lords, at which time he became the 1st Baron Kelvin. Lord Kelvin and James Joule worked together to develop the absolute thermodynamic temperature scale, now known as the Kelvin scale. They concluded that 'absolute zero' temperature is -273.15°C, or 0°K.

William Thomson, Lord Kelvin in Belfast Botanic Gardens, Northern Ireland

James Joule was born in Salford in 1818, the son of a local brewery owner. For much of his adult life, he managed the family brewing business. In parallel, he studied the nature of heat and its relationship with mechanical work. Like Einstein's theory of relativity connecting mass and energy, Joule made the link between the interchangeability of heat and work.

Joule's claims were initially ignored since he had neither a background in engineering nor academia. However, his theory led to the development of the first law of thermodynamics, arguably one of the most profound laws of physics and energy. Put simply, the first law implies that for mechanical and energy systems there is no such thing as a free lunch. Or, what you get out will always be equal to, or slightly less than what you put in.





KUSTEC Eagle 45 with R744 refrigerant (left) and KUSTEC Eagle 145 with R744 refrigerant (right)

can produce around 10 per month in its current facility. With an order pipeline of 40 units, this production capacity will become stretched if demand increases. °LAUDA stands ready to scale up manufacturing capacity as the market develops further.

Electrolysers are commonly used to produce hydrogen onsite for hydrogen refuelling stations. They also require chilling to remove process heat and to achieve effective drying of the hydrogen gas as it leaves the electrolyser. In addition to °LAUDA's HRS cooler manufacturing operations in Germany, they produce the Ultracool product range in Spain. These process coolers are ideal for integration into electrolyser systems.

Low GWP refrigerants

Achieving -40°C requires the use of a low-temperature refrigerant gas. R404A can be used for HRS chillers since it can achieve -45°C, but it has a global warming potential (GWP) of 3,922.

R449A is a fourth-generation HFO refrigerant gas with a lower GWP of 1,397 which has been used for low-temperature refrigeration for some years. To completely avoid the use of F-Gases, hydrogen gas coolers can be designed to use hydrocarbons such as propane (R290) or natural refrigerants such as carbon dioxide (R744) as the refrigerant gas. These changes will future-proof cooling equipment from any potential F-Gas bans that may emerge in the EU or elsewhere.

In Austria, KUSTEC has been producing hydrogen coolers for refuelling stations using CO_2 as the refrigerant gas for several years. CO_2 is commonly used as the refrigerant gas to cool supermarket freezer cabinets. It was also considered for use in cars for mobile air conditioning systems, but R1234YF now dominates this application.

In the KUSTEC hydrogen gas cooling system, the CO_2 is liquefied in a compression cycle. This cold liquid CO_2 is fed via insulated pipes to the hydrogen dispenser. A heat exchanger transfers the cold energy from the liquid CO_2 to the

Hydrogen charging point. Image © Resato International BV hydrogen gas. Vaporised CO_2 gas returns to the CO_2 liquefier equipment, and the cycle is repeated. In hydrogen refuelling systems where thermal energy storage is required, a larger aluminium block heat exchanger can be used to store cold energy from the vaporising CO_2.

At present, cooling hydrogen to -40°C is the common practice. However, it is likely that cooling to only -20°C will become more popular to avoid the need for low-temperature systems and decrease the energy consumption. The Society of Automotive Engineers (SAE) has published T40 and T20 Protocols in the J2601 series to allow for different pre-cooling temperatures at -40°C and -20°C.

The SAE is also considering additional refuelling protocols for cooling to -10°C and ambient temperature gas transfer. These will reduce the complexity of the cooling system.

Liquid hydrogen

When cryogenic liquid hydrogen is stored at the HRS, the thermal management may take a different approach. Liquid hydrogen is stored at around -253°C. If it is decanted directly into the vehicle to be stored as liquid onboard in a cryogenic tank, there is no need to vaporise or warm the liquid hydrogen.

If liquid hydrogen is used for storage at the HRS, but the vehicle tank is to receive high-


Hydrogen refuelling nozzle

Compressed hydrogen gas storage in a bus

pressure compressed gaseous hydrogen, the configuration becomes more complex. The liquid is pumped to the required pressure of around 450 bar for trucks and buses, or 850 bar for cars. These pressures allow a driving force into the storage tanks, which will operate at 350 bar and 700 bar, respectively.

The high-pressure liquid is then vaporised in a heat exchanger and enters a high-pressure gas storage bank. The warm energy for vaporisation may either come from ambient air or a water bath. The vaporisation can be controlled to ensure that the hydrogen is warmed to -40°C. As the gas leaves the high-pressure storage bank, it can be chilled against liquid hydrogen. In this case, no additional chiller is required.

About the author

Stephen B. Harrison is the founder and managing director of sbh4 GmbH in Germany. He focuses on decarbonisation technologies and strategies. Hydrogen and Power-to-X are fundamental pillars of his consulting practice. With a background that includes 27 years at BOC Gases, BOC Group, and Linde Gas, Stephen possesses an intimate knowledge of hydrogen from commercial, technical, operational, and safety perspectives. His expertise extends across the full length of the value chain, from production, purification, distribution, and storage through to utilisation.