Hydrogen refuelling dispenser

The Joule-Thomson effect

The science behind the need for chillers on hydrogen refuelling stations

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Why do some gases get hot when they expand as their pressure is reduced but others get cold in the same circumstances? And more confusingly, why does the same gas get cold when expanding within a certain pressure range and get hot when expanding in a different pressure range?

The answers lie in the Joule-Thomson effect. This thermodynamic principle can be used to liquefy air for cryogenic distillation or liquefy natural gas to LNG for transportation by ship. The Joule-Thomson effect is also behind the need to use a chiller to cool compressed gaseous hydrogen prior to it being filled into the storage tank on a boat, bus, truck, train, or car.

James Joule and William Thomson

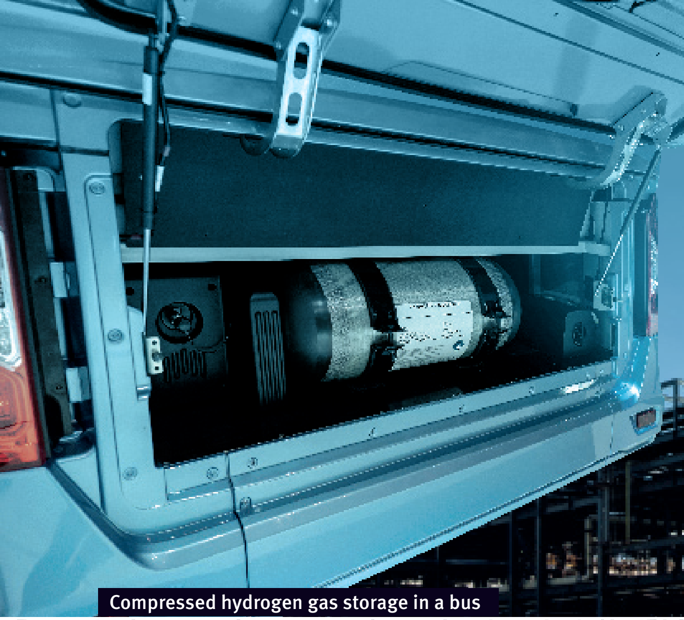
James Joule was born in Salford in 1818, the son of a local brewery owner. For much of his adult life, he managed the family brewing business. In parallel, he studied the nature of heat and its relationship with mechanical work. Like Einstein's theory of relativity connecting mass and energy, Joule made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

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 first 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.

The Joule-Thomson effect

When ammonia as a refrigerant gas expands from 14 bar to atmospheric



Compressed hydrogen gas storage in a bus

© APCI | **LNG Liquefier Main Coil Wound Heat Exchanger. Hanas China**

pressure it cools to around -33 °C. This principle is used in CO_2 liquefiers. Similarly, when propane acting as a refrigerant gas in an LNG refrigeration cycle is expanded from 10 to 1 bar, it cools from 30 °C to -30 °C.

On a nitrogen generator or air separation unit air flows through the expansion turbine. As it does so, it cools to provide the cryogenic temperatures required to separate the constituent gases of air through cryogenic distillation.

In all 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 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.

Compressed hydrogen gas is stored in the static intermediate pressure storage tanks on a hydrogen refuelling station (HRS) for buses or trucks at around 500 bar. For cars, the high-pressure storage on 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 over heated. 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.

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

Chillers for Hydrogen refuelling stations

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. Jasper Laug, Business Development Manager – Hydrogen at °LAUDA, says that "our HRS chillers are designed to cool hydrogen with a delta of around 100 °C, from plus 60 degrees to -40."

°LAUDA is a family-owned business with headquarters and manufacturing in Germany. It is a global leader in indirect hydrogen cooling systems, which use an intermediate heat transfer fluid to bring the cold from the chiller to the dispenser. Laug states that "our indirect chiller can be located away from hydrogen gas and the dispenser in a non-ATEX zone and leaving more space around the dispenser for vehicle movements. Furthermore, cold energy can be stored in the heat transfer fluid to ▶

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LAUDA HRS Cooler

smooth out the chilling requirements during refuelling.”

The chilling requirement at the early stages of filling is significantly more than during the later stages. There is also an operational interval between filling vehicles as they drive away from and approach the dispenser. This means that the chilling requirement is highly variable. “The use of the indirect chiller allows it to operate at the average chilling requirement, not the peak”, says Laug. “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. “Our order pipeline currently has 40 units for some extremely interesting projects”, confirms Laug. “We can produce around 10 per month in our current facility, but this is not sufficient to meet the demand that we are expecting, therefore we can expand our manufacturing capacity if the demand increases.”

PEM 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. Laug says that “in addition to our operations in German, we produce the Ultracool product range in Spain. These process chiller units are ideal to integrate into PEM electrolyser systems.”

> “PEM electrolysers are commonly used to produce hydrogen onsite for hydrogen refuelling stations”

Refrigerant selection

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.

Laug adds that “at °LAUDA, we have used the modern refrigerant gas R449A for some years. R449A is a fourth generation HFO refrigerant gas with a lower GWP of 1,397. However, future generations of our equipment will be designed to use hydrocarbons as the refrigerant gas to completely avoid the use of F-Gases.”

At present, chilling hydrogen to -40 °C is the common practice. However, it is likely that chilling to only -20 °C will become more popular to avoid the need for low temperature systems and decrease the energy consumption. In addition, it will reduce the complexity of the cooling system and future-proof our equipment from any potential F-Gas bans that may emerge in the EU or elsewhere.

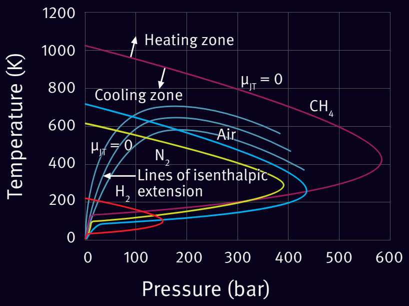
Thermal management on a liquid hydrogen refuelling station

When cryogenic liquid hydrogen is stored on 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 on board in a cryogenic tank, there is no need to vaporise or warm the liquid hydrogen.

If liquid hydrogen is used for storage on the HRS, but the vehicle tank is to receive high pressure compressed gaseous hydrogen the configuration is 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.

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

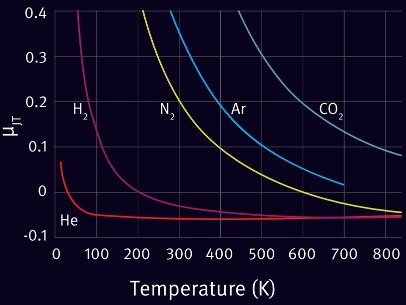
Joule-Thomson Inversion Curve



H_2 Hydrogen
N_2 Nitrogen
CH_4 Methane

He Helium
Ar Argon
CO_2 Carbon dioxide

μ_{JT} – Joule-Thomson coefficient (K/bar) and inversion temperatures at atmospheric pressure



$\mu_{JT} > 0$ means the gas will cool down during expansion

$\mu_{JT} < 0$ means the gas will warm up during expansion

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. gw