LINDE AG
Linde Gas Division

Linde Coupling and Refuelling System

Performance and Measuring Results

(Translation into English)

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1 Linde Coupling:

In this double flow cryogenic coupling system (figure 1) the process lines are positioned in parallel and within the coupling itself they are mounted in a coaxial way. The complete system is highly evacuated and super insulated. The connection for the cryogenic hydrogen between filling station and vehicle is established by ball valves. The ball valves are opened and closed by a gear drive.

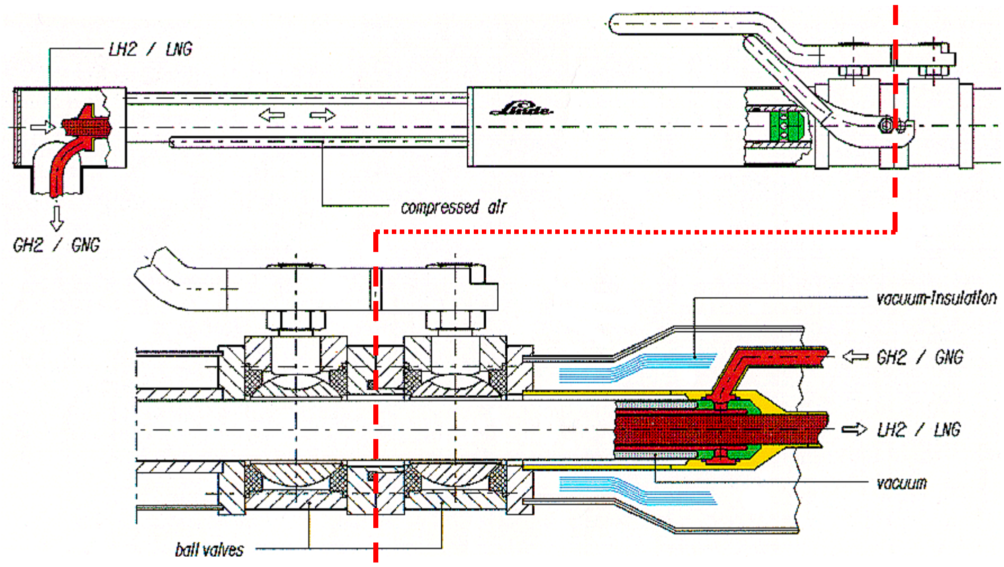

Figure 1: LH2- Coupling Principle, both ball valves opened

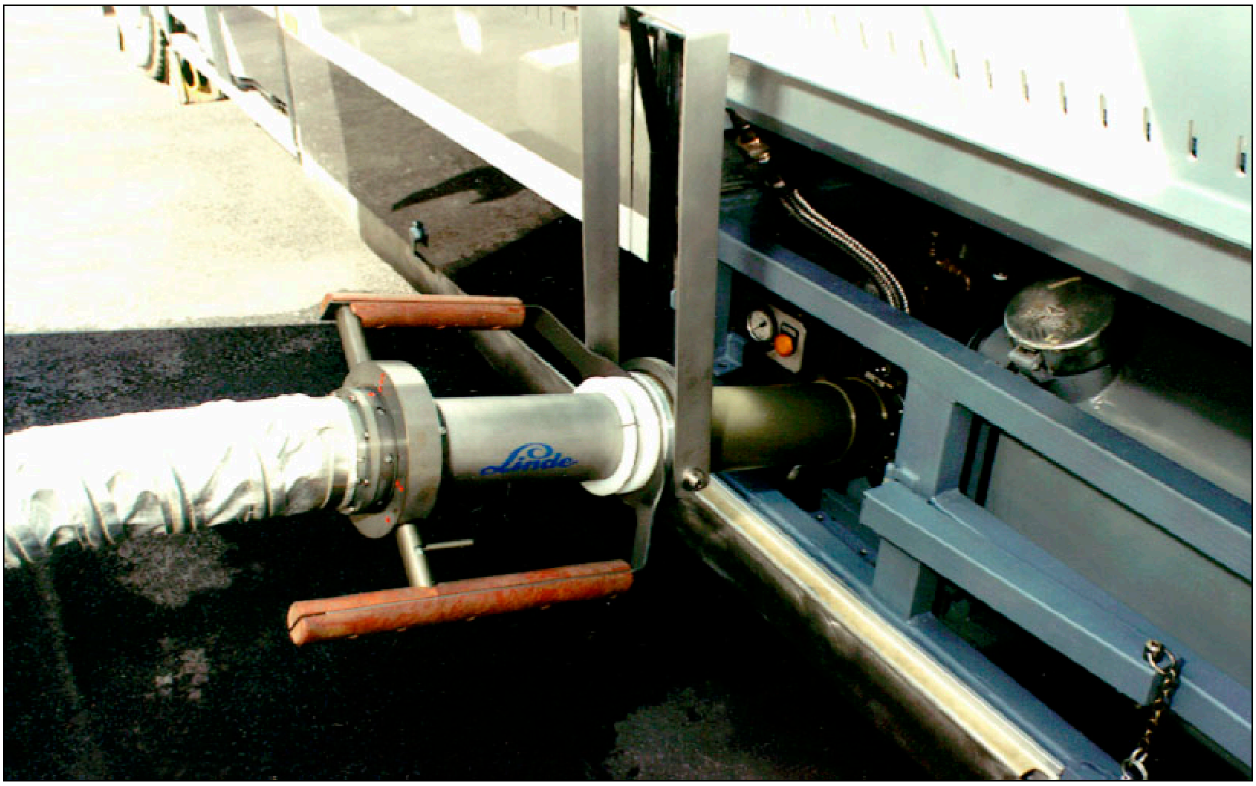

Figure 2: First generation LH2- Coupling 1994

The refuelling concept with the double flow cold traceable Linde LH2-coupling has already been tested in detail in the project: "Solar – Wasserstoff Bayern Projekts in Neunburg vorm Wald (SWB)" in 1995. The attribute "cold traceable" is used for the kind of coupling, because it makes secure a docking and undocking possible, while on both sides in the coupling (Filling station and vehicle) liquid hydrogen is standing.

Figure 2 shows the first generation double flow cold traceable Linde LH2-coupling.

The second generation is a further development stage. It has proven its suitability for every day use in over 4000 refuelling procedures at approximately 15 non-public filling stations, and the first public filling station (Munich airport) around the world.

At Munich Airport a second generation coupling is automatically driven by a robot in which it has been integrated.

The refuelling characteristics of both generations are identical. The difference between the first and the second generation bases on improved handling and smaller dimensions of the second generation.

Except before and after (dis)assembly works, as with the former generation, no evacuation or inerting is ever required for refuelling procedures with the Linde LH2 coupling system. Helium requirement is zero in normal use.

Figure 3: Second generation LH2- Coupling 1999

2 Liquid Hydrogen Refuelling

The main goals of a refuelling procedure are a short refuelling time, easy handling of the coupling, low refuelling losses and a short time requirement of the system to be operational for the next refuelling.

- Short refuelling time
- Easy handling of the coupling
- No or very low hydrogen losses
- Short time requirement to be operational for the next refuelling

In order to reach short refuelling times, without any hydrogen losses, a subcooled liquid is necessary.

Sub-cooled means that the actual temperature of the liquid hydrogen lies below the boiling point of liquid hydrogen.

Sub-cooling can only be effective when also the process lines have low pressure losses and the liquid hydrogen lines have a very good thermal isolation.

On top of that return gas free refuelling of a vehicle tank requires condensation of the gas cushion inside the vehicle tank.

2.1 Measurements during the “Solarwasserstoff Bayern” project

Within the boundaries of the “Solarwasserstoff Bayern (SWB) project in “Neunburg vorm Wald” a large number of refuelling measurements have been performed.

The tests in “Neunburg vorm Wald” have shown that a loss free refuelling procedure (no return gas) is only possible in case the whole refuelling system is in a pre-cooled state of <50K. The latter is a situation that cannot be held for future real filling stations, without extra cooling or pre-cooling. Series refuelling (see Chapter 2.2) at the Munich Airport public LH2 filling station have confirmed this.

On top of that there are requirements to the refuelling line inside the vehicle. The latter is always at more or less at ambient temperature. Therefore the line should have low weight and be as short as possible, in order to keep evaporation losses of liquid hydrogen by cooling of the lines as low as possible.

The following example (figure 4 and 5) shows the graphs of a refuelling procedure, where all the former described requirements have been kept:

- Refuelling system (including vehicle tank) in pre-cooled condition (<50 K)
- Very short and therefore lightweight vehicle side refuelling line (app. 20 cm)
- Sub-cooled liquid hydrogen for refuelling
- Before refuelling an empty, or almost empty vehicle tank system (<10% of tank volume)

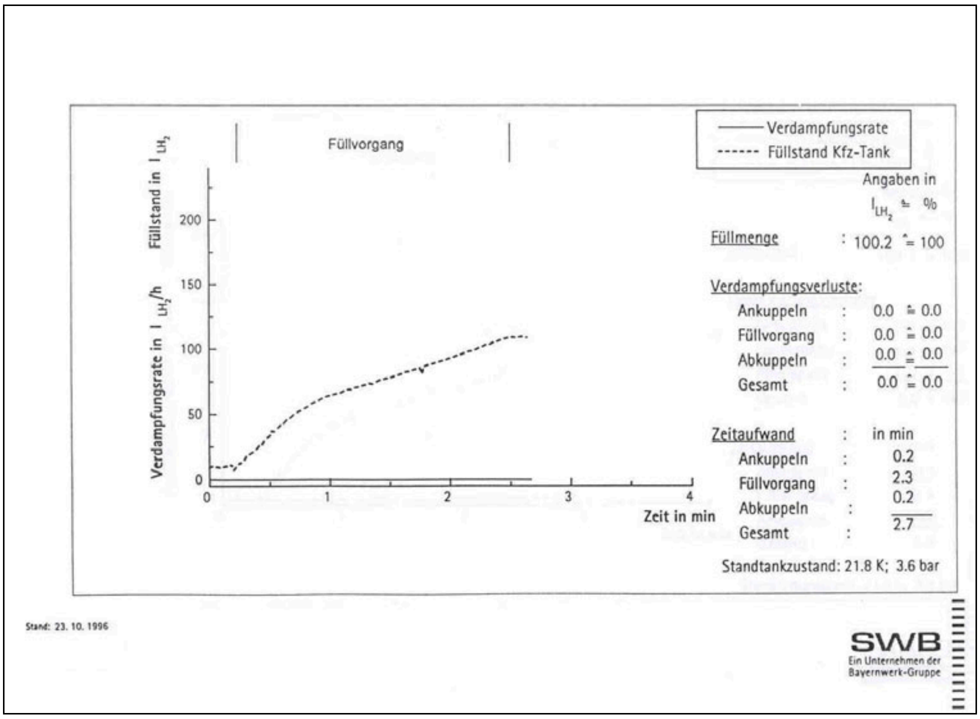

Figure 4: Loss free LH2- refuelling in "Neunburg vorm Wald"

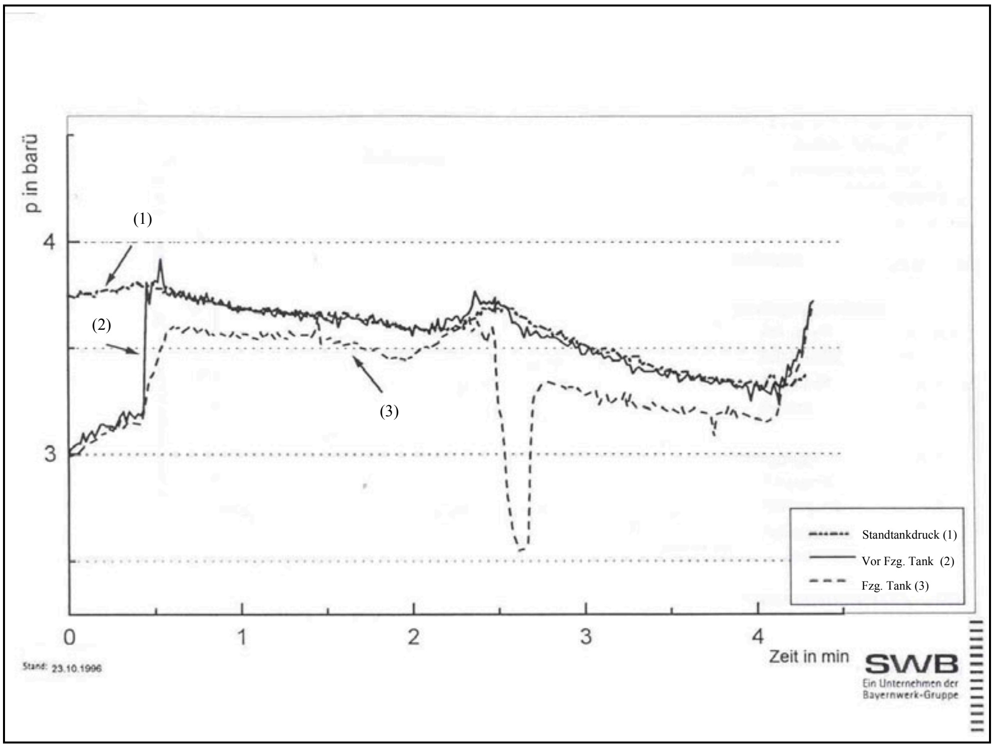

Figure 5: Loss free LH2- refuelling in "Neunburg vorm Wald"

For the tests the storage tank (volume app. 3000 litres) was conditioned to a temperature of app. 21.8 K and a pressure of app. 3.6 bar (pressure cushion principle).

The sub-cooled LH2 from the storage tank is sprayed onto the gas cushion inside the vehicle tank. A part of the gas cushion condensates on the surface of the LH2 drops that are sprayed into the vehicle tank, in case these drops are colder than the gas. By the resulting pressure drop a pressure difference between the storage tank and the vehicle tank, which is required for the refuelling process, remains. The latter makes a loss free refuelling procedure possible.

The results show that with this optimised refuelling setup using the Linde system an average flow rate of 100.2 litres in 2.3 minutes was reached at a total pressure loss in the refuelling system of less than 300 mbar.

An average flow rate of 2600 litres/ hour was reached. The maximum flow rate however is considerably more (app. 6000 litres /hour)

Basing on these positive results, a shown refuelling time of 2 to 3 minutes for a vehicle tank of 100 litres, can be stated that this flow rate is the minimum requirement for a comfortable refuelling procedure.

However the experiments have also shown that the optimal refuelling is only possible with the right set of technical conditions. The latter could only be established within the controlled environment and technical equipment at the particular test site.

Even with these experiments, where all efforts for appropriate pre-sets had been made, during some refuelling procedures, a pressure relief procedure had still to be carried out, in case an optimum refuelling was not possible. From Figure 6 can be seen, how a paused refuelling procedure is started again by a pressure relief. The latter refuelling was a one flow refuelling (blocked gas return line) with the double flow coupling.

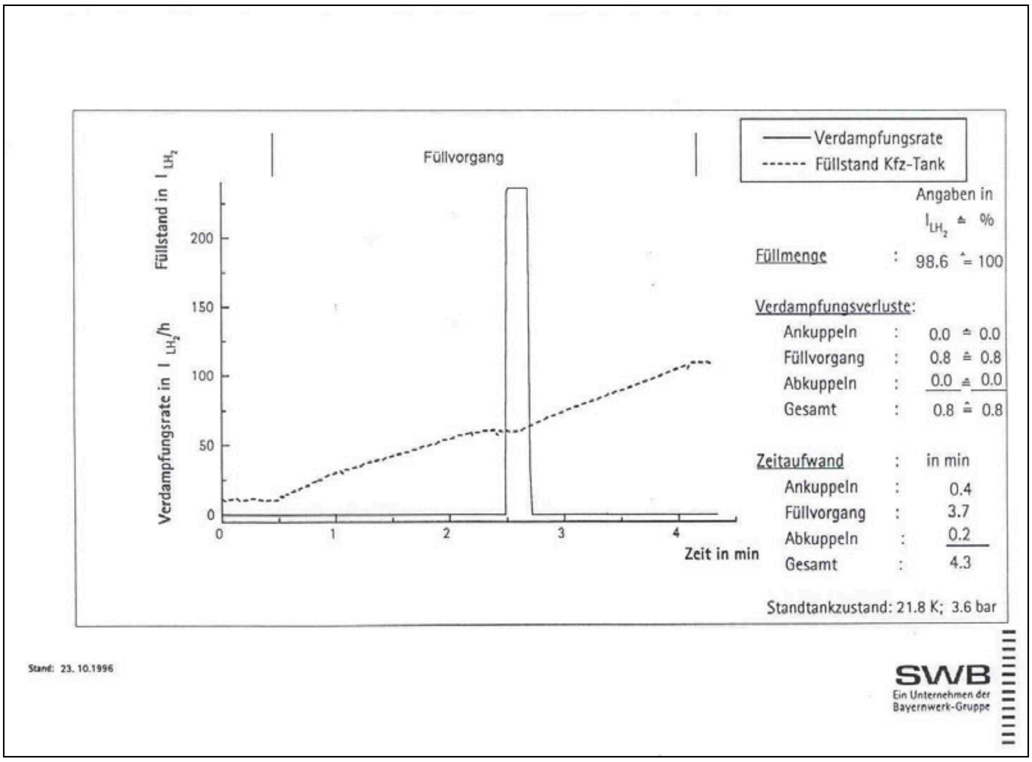

Figure 6: LH2- Refuelling in "Neunburg vorm Wald" with pressure relief

A double flow system allows, as can be seen from figure 6, even though a pressure relief action, low losses of time and hydrogen. No liquid hydrogen is lost. The refuelling procedure came to a halt because during these tests no pressure relief action during the refuelling itself was allowed at the same time.

Under real circumstances the optimal conditions described above are hard to be reached because for instance:

- no sub-cooled liquid hydrogen available for refuelling;
- the lines at a public filling station are much longer because of construction site requirements;
- the refuelling cycle time is too long (time interval until refuelling of a following vehicle). This causes a warming up of the refuelling lines;
- The refuelling line inside the vehicle (i.e. tank on top of a bus) is longer than in the set-up for the experiments.

Taking the latter points into account a single flow refuelling process causes a considerable pressure rise in the vehicle tank, because evaporated liquid from the filling line of the filling station side and the vehicle side is pressed into the gas room of the vehicle tank. The refuelling is automatically stopped by the pressure balancing between vehicle tank and storage tank.

With single flow refuelling the tank has to be pressure relieved via the (single flow) filling line, refuelling comes to a halt. After pressure relief the further refuelling with liquid hydrogen can be started again. In the renewed refuelling cycle liquid hydrogen from the filling station meets a filling line that has been warmed up by the return gas of the pressure relief and has to cool down the refuelling line again.

When pressure is relieved, remaining liquid hydrogen in the filling line has to be pressure relieved as well, and is therefore lost for refuelling.

Depending on the level of pre-conditioning and the state of the refuelling system, multiple refuelling cycles are required, which will result in longer refuelling times and an increased amount of return gas.

With double flow refuelling the liquid is pushed into the vehicle tank in one cycle. In case the refuelling system is not pre-conditioned in a optimum way, return gas can be sent back to the filing station in parallel to the actual refuelling. The refuelling procedure does not have to be cut in cycles. Liquid hydrogen in the lines will not be transferred back to the filling station. This is especially advantageous, in case the filling lines will have greater lengths for instance in public filling stations.

Important parameters for efficient refuelling procedures:

- Level of sub-cooling of hydrogen entering the system
- Length and weight of filling lines on the filling station side
- Occurrence of refuelling procedures
- Length and weight of filling lines on the vehicle side

2.2 Measurements within the boundaries of the "ARGEMUC" Project

Within the boundaries of the ARGEMUC project at Munich Airport a large number of refuelling measurements have been performed as well. It is the worlds first public filling station for liquid hydrogen.

For these experiments the vehicle tank was also filled without a pump, by pressure balancing. The "tank" from which was refuelled is a buffer storage vessel (volume app. 800 litres). This set up has been established to keep losses from each storage tank pressure relief as low as possible.

The main differences for evaluation of the test results compared to the SWB test site are:

- buffer vessel for pressure build up;
- longer refuelling lines (app. 19 metres);
- automatic refuelling by a robot (docking, and undocking times).

Measurements at the LH2 filling station at Munich Airport have shown, that a refuelling procedure free of return gas, with the required condensation effect in the vehicle tank, is in effect not earlier than after refuelling three vehicles (series refuelling) one after another. The reason for this lies in the long filling lines a public filling station like this one.

Figure 7 shows the behaviour of the refuelling system and the typical curve of a refuelling procedure during such a series refuelling.

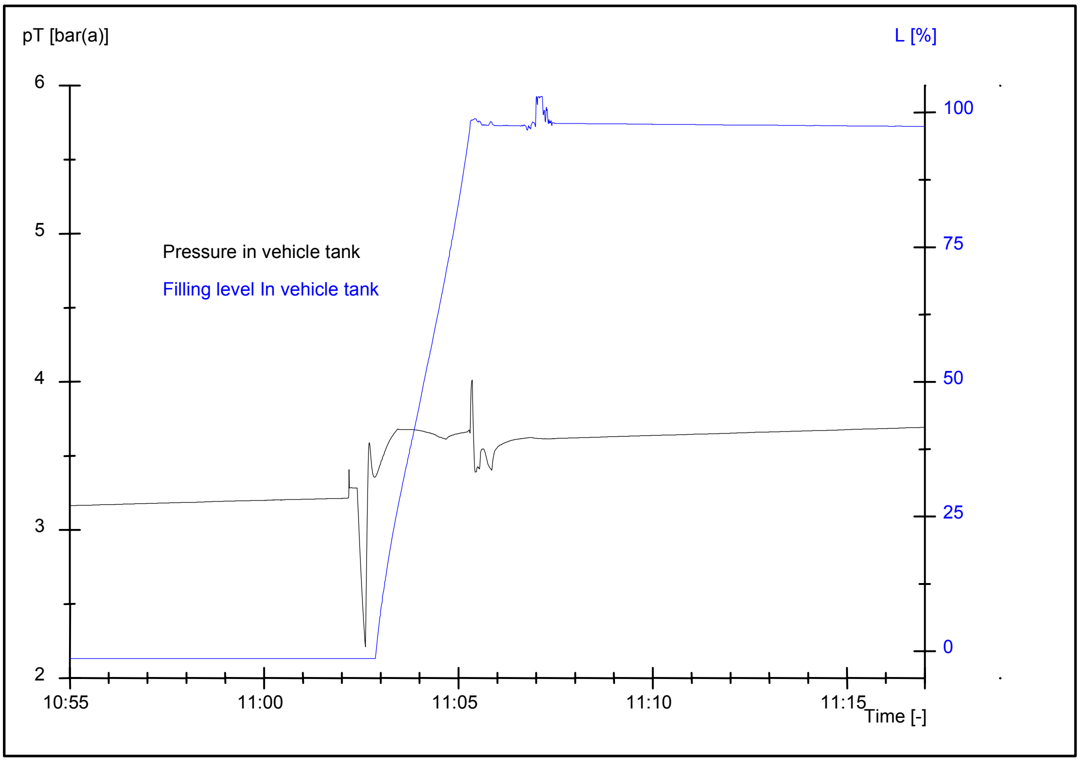

Figure 7: Refuelling 3 / 3rd vehicle

Refuelling at Munich Airport was performed, as with the SWB experiments, with sub-cooled liquid hydrogen. This was done by pressurising the liquid stored at low temperature in a vacuum insulated vessel (buffer).

From this buffer vessel up to six sub-cooled refuelling procedures are possible, depending on the filling level. After the buffer has been “emptied,” it is pressure relieved and refilled with cryogenic liquid by the larger storage tank.

The gas that has been formed by relieving the pressure of the buffer is compressed and used at the station. The installed flow metre, which is mounted in the filling line, shows that even with the relatively not so optimal configuration (long lines) flow rates of 3000 litres / hour are reached. The pressure loss in the system lies at app. 400 mbar, because of the longer lines.

With help of the patented Linde refuelling system one vehicle after the other could be refuelled without any pause. Between the refuelling of cars pauses of several minutes could be noticed. These stop times are not related to the refuelling system, they are caused by docking and undocking of the robot.

2.3 Sub-cooled refuelling with help of a transfer pump

In order to prevent pressure relief „losses“ at future filing stations, and to transfer liquid hydrogen continuously, Linde has developed a liquid hydrogen transfer pump. The pump can continuously provide sub-cooled hydrogen.

The pump is integrated in a LH2 vessel (volume app. 100 litres) and increases the pressure at the pump outlet. Heat transfer into the liquid is minimised by a dedicated construction. The liquid at the outlet of the pump is always sub-cooled.

Advantages of the LH2 pump are:

- Through the low pressure of the storage vessel very cold liquid (21.7 K) is provided
- With the LH2 pump liquid hydrogen, is provided, without any extra heat input as with formerly required conditioning actions, at a higher pressure as present in the vehicle tank. That means the refuelling works with sub-cooled liquid.
- In the refuelling lines there is only a single phase flow state therefore flow losses are minimised , refuelling time are shortened.
- The gas cushion in the vehicle tank condensates , which leads to a minimisation of return gas during refuelling, which also leads to shortened refuelling time.
- Refuelling is possible at all times independent of time schedule, and without any complicated conditioning measures.
- The possible number follow up refuelling procedures is restricted only by the volume of the main storage tank.
- Adjustable flow rate

3 Conclusions

A double flow coupling allows efficient (loss free) fast refuelling without loss of time by pressure relief actions. Double flow refuelling allows refuelling with a gas return in parallel.

Efficient refuelling procedures in unconditioned (real) situations require a double flow refuelling.

Real conditions that generally have a negative influence on a loss free refuelling procedure (If one or more of the following conditions occur, the vehicle tank most likely needs to be pressure relieved):

- LH2- filling line of vehicle is warm (ambient temperature). The filling line inside the vehicle is warm at all times and is cooled down during refuelling of liquid hydrogen. An increase of pressure in the vehicle tank caused by precedent heat input is more evident in vehicles with long refuelling lines (>800 mm). Without pressure balancing (taking gas return) the refuelling procedure comes to a halt.

- LH2 filling line of the filling station is warm (i.e. > 50K). Also during a series of refuelling procedures, (one vehicle after the other), the lines get warm in between the refuelling procedures. Pressure increase in the vehicle tank through precedent heat input in the entering hydrogen is more evident at filling stations with long LH2 filling lines. Without pressure balancing (taking gas return) the refuelling procedure comes to a halt.

- Vehicle tank is warm (ambient temperature). Pressure increase in the vehicle tank through immediate heating up and evaporation of the entering hydrogen. Without pressure balancing (taking gas return) the refuelling procedure comes to a halt.

- Relatively full vehicle tank (filling level around 70% or more). The gas cushion cannot condensate to the right extent (see also refuelling curves in figure 4). The high filling level does not allow a proper heat exchange between the LH2 drops and the gas cushion. For single flow refuelling the gas room is too small to accommodate the gas that comes in front of, and is pushed by, the entering liquid.

Compared to single flow refuelling procedures less time and hydrogen are lost with double flow refuelling procedures.

If necessary double flow constructions allow for a pressure relief action during refuelling.

With single flow refuelling, the refuelling procedure must be stopped to relief the pressure of the vehicle tank. LH2 has to go back through the filling line in order to relieve the pressure. Doing this the latter liquid hydrogen is lost. The pressure relief action must possibly be repeated several times before refuelling starts again.