MEASUREMENT METHODS FOR GASEOUS HYDROGEN SUPPLY BY TRAILERS

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Table of Contents

1 Introduction 1
2 Scope 1
3 Definitions 1
3.1 Publications terminology 1
3.2 Technical definitions 2
4 Delivered gas by mass calculation from Pressure and Temperature (PT) measurements 3
5 Measurement of delivered gas by integration of mass flow rate 4
6 Measurement of delivered gas by weight 5
6.1 Weight cells at trailer or customer installation 6
6.2 Weight bridges 6
7 Comparison of the reviewed measurement methods 7
8 References 8
Appendix A: Volume tolerances for Hydrogen pressure receptacles 9
Appendix B: Example of uncertainty calculation for PT method 10

Table 1 - Characteristics and operating conditions for certified flowmeters in Germany by PTB (Physikalisch-Technische Bundesanstalt National Metrological Institute) 5
Table 2 - Advantages and concerns for the different approaches to evaluate the hydrogen mass for transaction 7

Figure B1 - Measurement uncertainty of transferred mass in percentage for different pressure measurement accuracy 10
Figure B2 - Measurement uncertainty of transferred mass in percentage for different temperature measurement accuracy 11

1 Introduction

The growing requirement for hydrogen as a key element in the energy transition and resilience necessitates unparalleled advancements to establish a robust and optimized end-to-end supply chain. This document concentrates on the principles of legislative metrology, which dictate the quantification of deliveries in commercial exchanges. This document focuses on the measurement options for quantifying gaseous hydrogen delivered by trailers. These transfer measurement methods will be analysed within the scope of this document.

All member states of the European Community have integrated into their legal systems the imperative for regulating all commercial transactions, yet a detailed specification for the delivery of gaseous hydrogen by trailers in industry is absent.

The current Measuring Instruments Directive (MID) [1] does not explicitly cover hydrogen measuring instruments for hydrogen transfer from trailers. The OIML R139-1 [2] and R139-2 [3] used for hydrogen dispensing to vehicles recommends measuring the transferred hydrogen mass with an accuracy 1.5%. A clear legislative guidance is still pending.

Therefore, this document provides an essential interim guidance on the subject. Identifying a reliable and safe method for measuring the transferred mass of gaseous hydrogen is critical. While primarily applied for new projects, this guidance may also be extended to retrofitting existing installations, as required in some EU countries. The recommended method ensures the necessary accuracy while balancing economic considerations.

2 Scope

With the growing volume of hydrogen being transferred, accurate measurement of delivered gas is of great importance. This document focuses on the delivery of gaseous hydrogen to Hydrogen Refueling Station (HRS). There are two primary delivery configurations considered:

- stationary trailer at the customer site (swap trailer),
- trailer unloading into a customer buffer system.

In the gas industry three main methodologies can be used to determine the amount of gas delivered. This document outlines these methods and presents their advantages and limitations. These methodologies are:

- mass calculated from density difference based on Pressure and Temperature measurement (PT),
- mass flow measurement using flowmeters,
- weight measurement using calibrated scale.

This document provides an overview of the existing methods used to quantify the delivered gaseous hydrogen, highlighting their advantages and potential constraints.

3 Definitions

3.1 Publications terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May and need not

Indicate that the procedure is optional.

3.1.4 Will

Is used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

3.2 Technical definitions

For the purpose of this publication, the following definitions apply:

3.2.1 Hydrogen trailer

Hydrogen trailers can be:

- Tube trailers which is a common name for battery vehicles defined in ADR (1.2.1) [4] as a vehicle containing elements, such as cylinders or tubes of different types (type I, II, III, IV), which are linked to each other by manifold and permanently fixed to this vehicle. The typical operating pressure is between 200bar and 380bar, but lower and higher pressures are existing.
- Multi-Element Gas Containers (MEGC) which are defined by ADR (1.2.1) [4] as a unit containing elements, such as cylinders or tubes of different types (type I, II, III, IV), which are linked to each other by manifold and mounted to the frame demountable from the chassis. The same operating pressure as for tube trailers applies.

3.2.2 Hydrogen Refueling Station

Facility for dispensing compressed hydrogen fuel to vehicles, often referred to as a hydrogen refueling station (HRS) or hydrogen filling station, including the supply of hydrogen, and hydrogen compression, storage, and dispensing systems (see ISO 19880-1 [5]).

3.2.3 Coriolis flow meter

Coriolis flow meters operation is based on the principles of motion mechanics. As the fluid moves through a vibrating tube, the fluid is forced to accelerate as it moves toward the point of peak-amplitude vibration. Conversely, decelerating fluid moves away from the point of peak amplitude as it exits the tube. The result is a twisting deformation of the flow tube during flowing conditions as it traverses each vibration cycle. The degree of the twist correlates with the mass flow rate. These flowmeters offer high accuracy and direct mass flow measurements.

3.2.4 Differential pressure flow meter

A differential pressure is measured across an obstruction (flow restriction) such as an orifice plate. The differential pressure enables to determine a volume flow. Using Bernoulli equation and pressure temperature compensation, the volume can be determined and converted into a mass flow. This method requires accurate pressure and temperature measurements.

4 Delivered gas by mass calculation from Pressure and Temperature (PT) measurements

In the gas industry measuring the Pressure and Temperature (PT) to calculate the density is the most widely adopted method to obtain the mass of gaseous hydrogen delivered from a trailer. The mass of gas is calculated based on the change of density before and after delivery. The water capacity of the trailer or its sections is typically provided by the trailer manufacturer or trailer operator and will increase with pressure for type IV cylinders / tubes. See Appendix A for details.

The pressure can be measured manually using pressure gauge or automatically using pressure transmitter, which is a preferable method to improve accuracy and reduce human error. The instrument should be selected based on the pressure range of the application. The accuracy of the instrument used is determined by its class and should meet the required precision to minimize measurement uncertainty.

The temperature is typically measured using thermocouple or a resistive temperature sensor (e.g. PT100, PT1000). In general, the uncertainty can vary between 0.2 K and 1.2 K depending on the class of the instrument (e.g. IEC 60751 [6]). The operating temperature range for cylinders and tubes is normally in the range -40°C to +65°C, according to ADR chapter 6.2.2.1.6 and 6.2.2.1.7 [4].

There are three main options to measure temperatures:

- measuring the ambient air temperature
- measuring the surface temperature of cylinders or tubes
- measuring the temperature of the gas inside the cylinders or tubes.

It is essential to define the temperature value which accurately represents the average temperature of the gas in the trailer. The temperature may vary due to potential temperature gradients during operation, therefore gas stabilization time is required after unloading. These factors may result in discrepancies between measured and actual average gas temperature, contributing to uncertainty when calculating the density of hydrogen and ultimately the uncertainty in the unloaded mass of hydrogen.

To determine hydrogen density, it is necessary to use the real gas law equation that takes into account the compressibility factor of hydrogen. For the selection of the correct compressibility factor, it is recommended to use the NIST table (National Institute of Standards and Technology) [7], [8]. The real gas law equation to be used is:

$$m = \frac{P * V * M}{R * Z * T}$$

where:
m: Hydrogen mass, kg
M: Hydrogen molar mass, kg/mol
R: Perfect gas constant, J / mol
T: Hydrogen gas temperature, K
Z: Hydrogen gas compressibility factor
P: Hydrogen gas pressure, Pa
V: Total internal volume of the trailer, m^3

The uncertainty on the gas mass $\frac{\delta m}{m}$ calculation using the density obtained through the real gas law can be calculated as follows:

$$\frac{\delta m}{m} = \sqrt{\left(\frac{\delta T}{T}\right)^2 + \left(\frac{\delta Z}{Z}\right)^2 + \left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta V}{V}\right)^2}$$

The uncertainty of the compressibility factor Z is approximately 0.5% and is derived from two primary sources of uncertainty:

1. The uncertainty on the Equation of State (EoS) used to calculate the compressibility factor Z is in the order of 0.01% within the specified pressure and temperature range [8].
2. The propagation of the pressure and temperature uncertainties on the EoS used to calculate the compressibility factor. The order of magnitude of this uncertainty depends on the temperature and pressure uncertainties.

The dominant source of uncertainty in mass determination remains the accuracy of temperature and pressure measurements, see Appendix B showing an example of uncertainty calculation.

Considerations:

- The PT method becomes more complex when applied to composite cylinders. For Type IV cylinders/tubes it may not be sufficient to measure the ambient air temperature or surface temperature. Therefore, temperature measurement inside one or more cylinders/tubes may be required.
- In case of closed or isolated sections on the trailer, the change in effective water capacity shall be taken into account, when calculating the delivered mass of hydrogen.
- The dominant sources of uncertainty are temperature and pressure measuring methods/procedures.
- The manufacturing volume tolerances of cylinders / tubes can be accounted for considering individual volumes of each cylinder / tube as provided by the manufacturer.
- The volume change of type IV cylinders / tubes related to pressure needs to be accounted for.
- For cascade unloading systems, at least one temperature and one pressure measurement in each section may be necessary.

The main advantages of this method are:

- The method of calculating gas mass from Pressure and Temperature (PT) and Volume is currently widely adopted in the gas industry, due to its reliability and cost effectiveness.
- The PT method allows automated and real time mass calculation.
- Independence of the withdrawal flow rate range.
- The measurement system requires calibration of the temperature and pressure sensors, but this is less expensive than calibration of flowmeters.
- Significantly lower purchase and maintenance costs of PT measuring instruments compared to flowmeters.
- Pressure and temperature sensors are widely used and can often be installed with minimal piping modifications reducing potential leaks, trailer immobilization downtime, and associated safety concerns.

Metering industry is working on this topic to improve the accuracy of measurement with the goal to develop a certified solution.

5 Measurement of delivered gas by integration of mass flow rate

A dynamic metering system can be used to determine the mass or volume of gas transferred between two points typically from delivery hydrogen trailer to customer tank or customer installation for swap. The most common technologies are Coriolis and Differential Pressure Flowmeters. Mass flowmeter such as Coriolis requires less data treatment afterwards.

The operational conditions of a flowmeter shall align with the requirements and specifications of the intended applications. Most important requirements are described in ADR [4], MID [1] and OIML 137 [9], ATEX [10], Transportable Pressure Equipment Directive [11] and additional local regulations.

Flowmeters should be capable of delivering reliable and accurate reading across the whole expected flow and pressure ranges. Like any other instruments, flowmeters require calibration to maintain the measurement accuracy. Preventive maintenance should be considered at the time of installation to minimize operational downtime and ensure the system remains compliant throughout its lifetime. The flowmeter and its installation should be robust enough to resist mechanical stress and vibrations of trailer movement without losing accuracy.

Application study:

Typical customer consumption for trailer swap or delivery to on-site stationary systems is between 5 Nm^3/h to 2750 Nm^3/h.

For official billing of gaseous hydrogen from trailers, flowmeters are only implemented by legislation in a limited number of countries (eg: Germany and Austria). There is no certified flowmeter on the market that covers the full range of typical flow rates. With further development it would be possible to combine several flowmeters to cover the full range.

Following flowmeters were evaluated:

- Type A based on Coriolis;
- Type B based on differential pressure.

The operation conditions and limits are shown in Table 1. The minimum flowrates of the considered flowmeters are limited to 713 Nm³/h (for 210 bar) and 936 Nm³/h (for 1000 bar) and therefore higher than required for this application. Below the minimum flow rate the accuracy of the devices is not defined and an inaccurate measure of hydrogen quantity might occur. Under the cut off value, the flow meter stops reading, which corresponds to 350 Nm³/h for 200 bar and 576 Nm³/h for 1000 bar. As none of the selected devices will show values, this would lead to significant billing losses for the Hydrogen supplier.

Considerations:

- The considered flowmeters do not have an appropriate range for the required customer delivery.
- The differential pressure flowmeter looked at is limited to 210 bar while modern trailers are designed for 300 bar and above.
- The retrofit or new installation of a flow meter system at a hydrogen trailer would add cost to investment and maintenance and therefore increase the price of hydrogen.

The main advantages of this method are:

- Flowmeters enable on site and immediate measurements of hydrogen delivery at the point of use.
- Flow meters are used in dispensers of HRS for recognized transactions (OIML R139 [2] and [3]) and are approved in Germany as a possible solution for gas counting.

	Type A	Type B
Flow rate range	Q_{min}: 936m3/h Q_T*: 3744m3/h Q_{max}: 18720m3/h	Q_{min}: 713m3/h Q_T*: 2854m3/h Q_{max}: 14268m3/h
Accuracy	Q_{min} to Q_T* = 1,5% Q_T to Q_{max} = 2,5%	Q_{min} to Q_T* = 1,5% Q_T to Q_{max} = 2,5%
Mini / Max Pressure	20bar / 1000 bar	10bar / 210 bar
Cut off	576 m3/h	357 m3/h
Ambient temperature range	-25°C / 55°C	-25°C / 55°C
Gas temperature range	-40°C / 55°C	-40°C / 40°C

*(Q= flow rate ; Q_T = flow rate at transition)

Table 1 - Characteristics and operating conditions for certified flowmeters in Germany by PTB (Physikalisch-Technische Bundesanstalt National Metrological Institute)

6 Measurement of delivered gas by weight

In general, the total weight of a trailer is considerably higher than the weight of transported gaseous hydrogen. Considering a typical total gross weight of 40 tons for a combination of tractor and trailer, the payload of GH2 transported is less than 2.5% of the fully loaded trailer (300kg -1000kg of GH2).

For example, for the usable mass of hydrogen of 800 kg the OIML R139 [2, 3] requires measuring the weight of hydrogen with an accuracy of 12kg for 1.5% trailer mass or 16 kg for 2% of the trailer mass.

There are two different approaches for measuring the trailer mass: by weight cells and weight bridges.

6.1 Weight cells at trailer or customer installation

There are two solutions to work with weight cells, one is to have them mounted directly between the trailer chassis and the trailer tube/cylinders or mounted between the ground and the customer buffer/stationary storage tank. Weather conditions or debris may influence the accuracy of measurements due to additional weight e.g. by ice, snow, rain or dirt.

Conclusion:
Due to practical and economic reasons, this method is not commonly used in the gas industry for gaseous hydrogen transport in trailers.

6.2 Weight bridges

The weighbridges used today have a scale of e=20kg. The Maximum Tolerated Error (MTE) of these weighbridges is 1.5*e = 30kg upon commissioning, or after a repair or periodic overhaul.

The annual periodic verification authorizes a Maximum Permissible Error (MPE) of 2*1.5*e = 60kg. A periodic overhaul on these bridges is mandatory every two years aimed at reducing the MPE to 1.5*e = 30kg.

Conclusion:
The weighing instruments for 28 tons trailer are currently very difficult and costly to meet the accuracy (eg 5kg resolution) required for transactional metering of hydrogen, especially for the transfer of small quantities of gas.

7 Comparison of the reviewed measurement methods

Table 2 summarises the advantages and concerns for the discussed approaches for evaluation of the transferred hydrogen from trailer to customer.

Approach	Advantages	Concerns
P and T measurement	The method is calculating the mass from P, T and Volume and is currently most used in gas industry, being reliable and cost effective. Independence of the withdrawal flow rate range Simple calibration process Significantly lower purchase and maintenance costs compared to flow meters Minor retrofitting of trailer required	Measuring surface temperature may be insufficient for type IV cylinders/tubes as gas temperature might change during delivery. The effective water capacity of the trailer during the delivery shall be known (might change in case of operation in cascade mode or in case of Type IV cylinders/tubes). Sensor P and T accuracy shall be carefully chosen to minimise the uncertainty. Multiple devices might be needed on different sections of the trailer. There is no existing legal reference for certification.
Measurement of delivered gas by integration of mass flow rate	Enable on site and immediate measurements of hydrogen delivery at the point of use. Already used : at HRS dispenser for recognized transactions globally for trailer / customer delivery in Germany	Existing certified solutions do not meet the required flow rate ranges of customer applications. The integration of flowmeters on trailers will include major costs for investment and maintenance. Only few flowmeters meet the requirements of ADR [4].
Measurement by weight	Laboratory or controlled environment only since it is very accurate for small quantities	Accuracy of measurements influenced by additional weight e.g. ice, snow, rain or dirt. Weighing instruments do not meet the accuracy for industrial applications.

Table 2 - Advantages and concerns for the different approaches to evaluate the hydrogen mass for transaction

8 References

Unless otherwise specified, the latest edition shall apply.

[1] Directive 2014/32/EU *on the harmonisation of the laws of the Member States relating to the making available on the market of measuring instruments,* https://eur-lex.europa.eu

[2] OIML R 139-1 International Recommendation *Compressed gaseous fuel measuring systems for vehicles. Part 1: Metrological and technical requirements,* (Organisation Internationale de Métrologie Légale) https://www.oiml.org

[3] OIML R 139-2 International Recommendation *Compressed gaseous fuel measuring systems for vehicles. Part 2: Metrological controls and performance tests*, (Organisation Internationale de Métrologie Légale) https://www.oiml.org

[4] ADR 2025 - *Agreement concerning the International Carriage of Dangerous Goods by Road,* https://unece.org

[5] ISO 19880-1 *Gaseous hydrogen — Fueling stations Part 1: General requirements, https://www.iso.org*

[6] IEC 60751:2022 *Industrial platinum resistance thermometers and platinum temperature sensors,*https://www.iec.ch

[7] NIST Web Book de Chemie, National Institute of Standards and Technology, SRD 69. www.webbook.nist.gov

[8] Eric W. Lemmon, Marcia L. Huber, Jacob W. and Jacob W. Leachman, *Revised Standardized Equation for Hydrogen Gas Densities for Fuel Consumption Applications*, [J. Res. Natl. Inst. Stand. Technol. 113, 341-350 (2008)] https://nvlpubs.nist.gov

[9] OIML R 137-1 & 2 International Recommendation *Gas meters Part 1: Metrological and technical requirements Part 2: Metrological controls and performance tests*, (Organisation Internationale de Métrologie Légale), https://www.oiml.org

[10] Directive 2014/34/EU *on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres,* https://eur-lex.europa.eu

[11] Directive 2010/35/EU *on transportable pressure equipment*, https://eur-lex.europa.eu

[12] EN 17339:2020 *Transportable gas cylinders – Fully wrapped carbon composite cylinders and tubes for hydrogen,* https://unece.org

Appendix A: Volume tolerances for Hydrogen pressure receptacles

There are two variations of volume for cylinders to be considered, the manufacturing tolerance and the variation of volume by pressure during loading and unloading and both need to be taken into account. The manufacturing tolerance is given by the manufacturer for each individual cylinder as requested by EN 17339 [12]. The fabrication volume tolerance may vary based on cylinder types:

- Seamless Type1 cylinder typical tolerance for up to 50l cylinders: +5%/-0%
- Type IV cylinders typical tolerance: +0/-20l or -15l (which is around 5%).

For type IV cylinders, the volume changes also due to pressure. This variation may be from 1.5 to 2.5%.

The volume of high-pressure type IV cylinders / tubes exhibits an almost linear increase with pressure p. Therefore, the volume V as a function of pressure is commonly modeled by the equation: $V(p) = C * V(p_o) * p/p_o$. Where $V(p_o)$ is the volume at a reference pressure p_o and C represents a constant factor specific to the cylinder or tube given by the manufacturer.
The volume of type IV cylinders does not change significantly with temperature since carbon fibers have a thermal length coefficient smaller than metals, almost zero.

To reliably achieve a targeted measurement uncertainty of 2.5% for the transferred mass, it is recommended that the volume variation with pressure should be accounted for.

Appendix B: Example of uncertainty calculation for PT method

The following scenario is chosen to illustrate the effect of temperature and pressure accuracy on the calculated mass transferred:

- trailer arrives at customer site with pressure in the range between 280 and 310bar;
- trailer leaves customer site with pressure in the range between 50 and 200bar;
- temperature range considered in the range between -10°C and 40°C
- the water capacity of the trailer is 39.9 m³.

Example: Unloading a trailer from 300 bar at 30°C down to 50 bar at 15°C corresponds to a transferred mass of 644.7 kg.
A pressure accuracy from ±0.025% to ±1% at full scale of 400bar of the pressure transmitter would correspond to ±0.1 bar to ±4 bar. See Figure B1.
For temperature accuracy of 1 to 4°C see Figure B2.

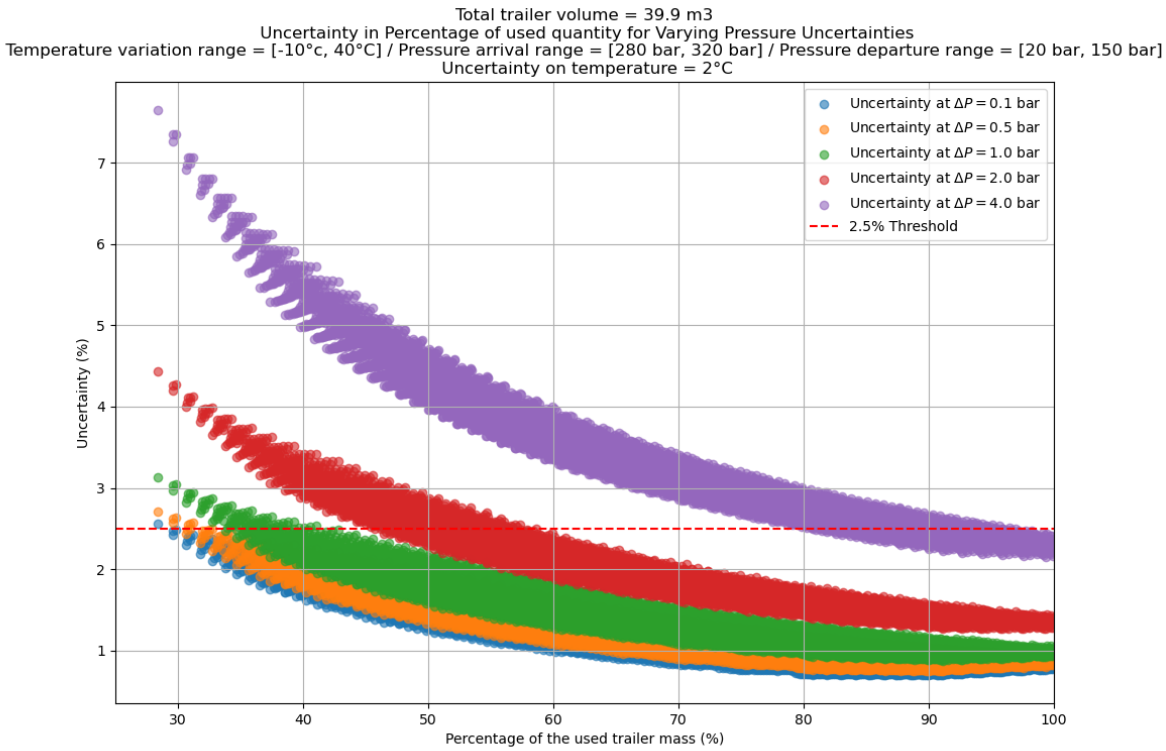


Figure B1 - Measurement uncertainty of transferred mass in percentage for different pressure measurement accuracy

Figure B1 shows how uncertainty in pressure measurements impacts the accuracy of the calculated mass of transferred hydrogen to meet the target uncertainty of 2.5% (red horizontal dotted line on the figure). A large amount of gas must be transferred if the pressure uncertainty is high: almost 100% of the mass has to be transferred for the pressure uncertainty of 4bar. A low-pressure uncertainty (1 bar or less) ensures reliable measurement of much smaller mass. Therefore, proper pressure measurement is highly important for accurately calculating the transferred hydrogen mass.

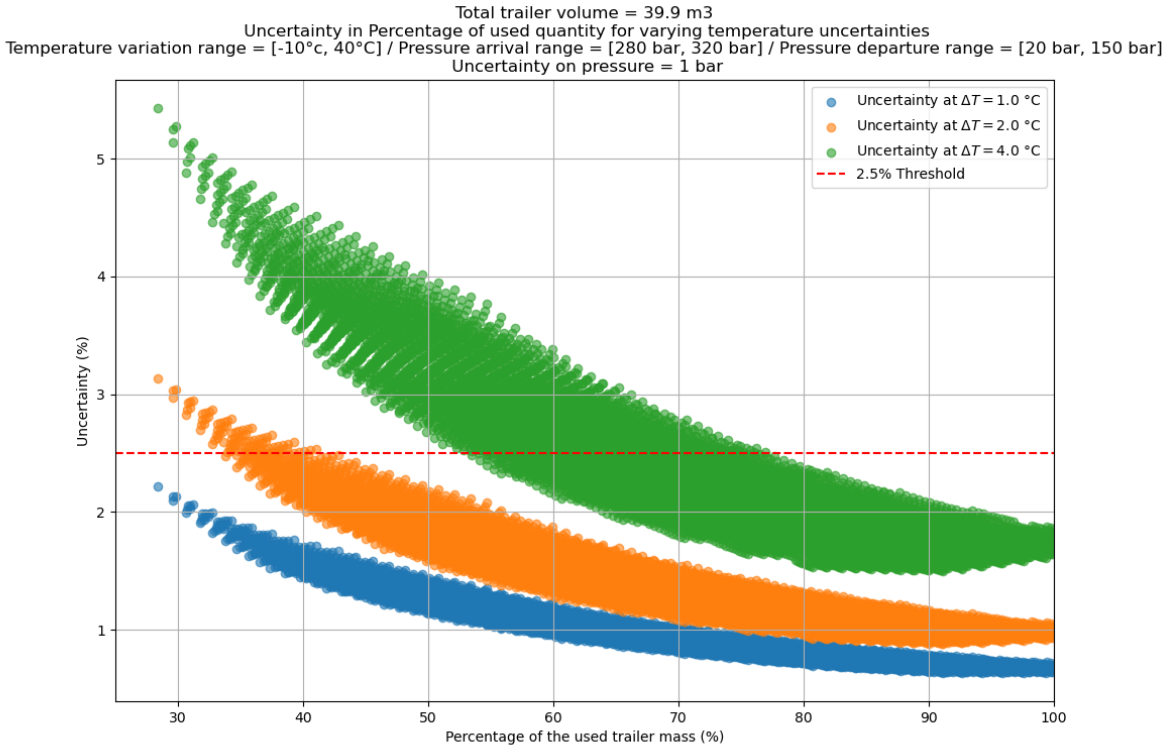


Figure B2 - Measurement uncertainty of transferred mass in percentage for different temperature measurement accuracy

Figure B2 shows how uncertainty in temperature measurements impacts the accuracy of the calculated mass of transferred hydrogen to meet the target uncertainty of 2.5% (red horizontal dotted line on the figure). A large amount of gas must be transferred if the temperature uncertainty is high: almost 80% of the mass has to be transferred for the temperature uncertainty of 4°C. A low temperature uncertainty (2°C or less) ensures reliable measurement of much smaller mass. Therefore, proper temperature measurement is highly important for accurately calculating the transferred hydrogen mass.