Metering of High Purity Hydrogen Gas using Versatile Ultrasonic Meters

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Agenda

- → Technical challenges of measuring high purity hydrogen with ultrasonic meters, and how these can be met
- → The aims and scope of the DNV H_2Met Joint Industry Project
- → Preparation of the meter prior to the JIP tests
  - – Liquid calibration of a gas meter?
- → Test results
- → Discussion
- → Conclusions

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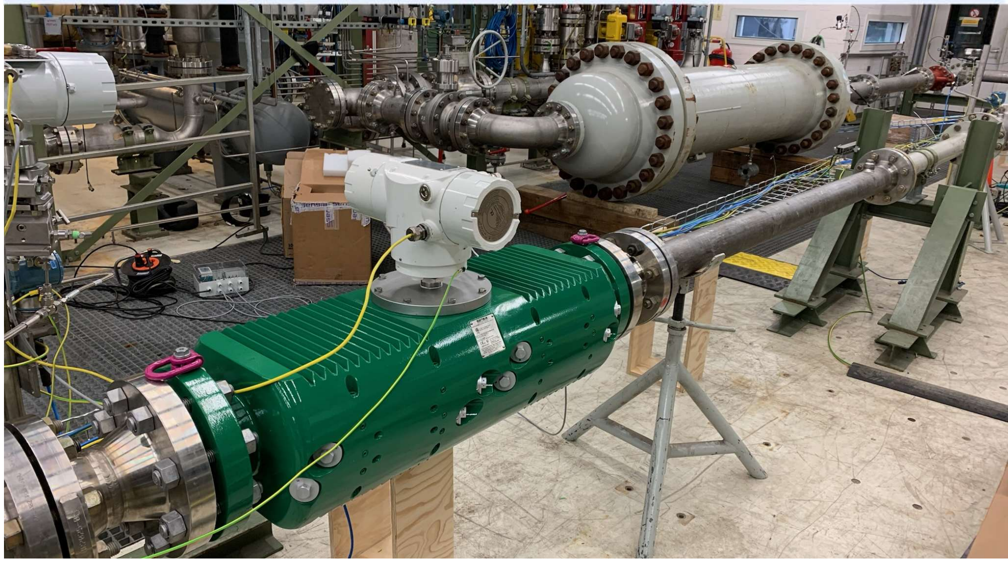
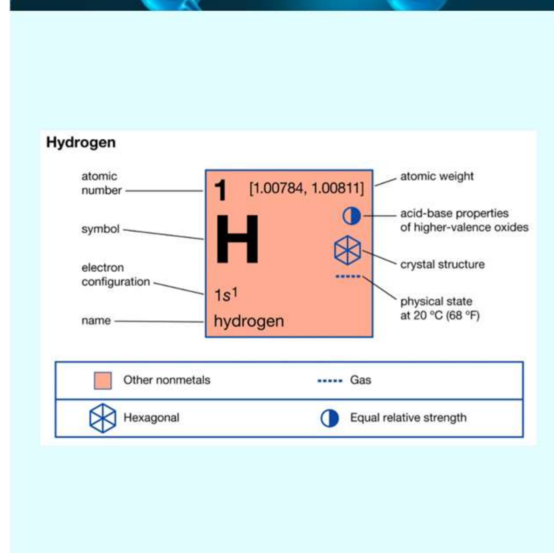


Hydrogen properties

→ Low density
  - Approx. 9 times lower than natural gas
  - At 450 psi (31 bar) approx. 400 times lower than water

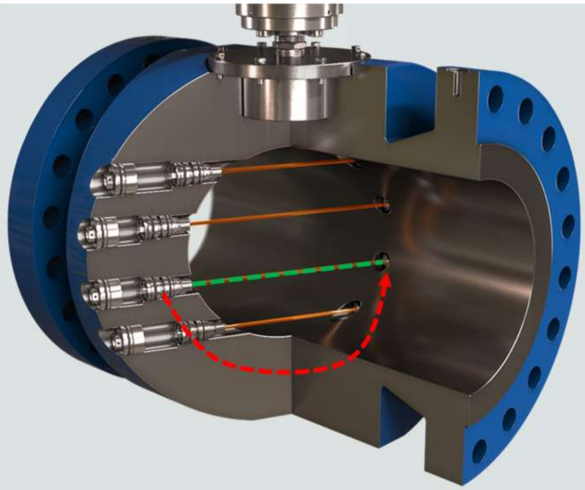
→ High speed of sound, *c*
  - Approx. 3 times higher than natural gas
  - More like a liquid SOS, approximately 4300 ft/s (1300 m/s)

→ Lower dynamic viscosity (~0.75 of natural gas) but significantly higher kinematic viscosity
  - Reynolds number typically 7 times lower than natural gas at the same velocity

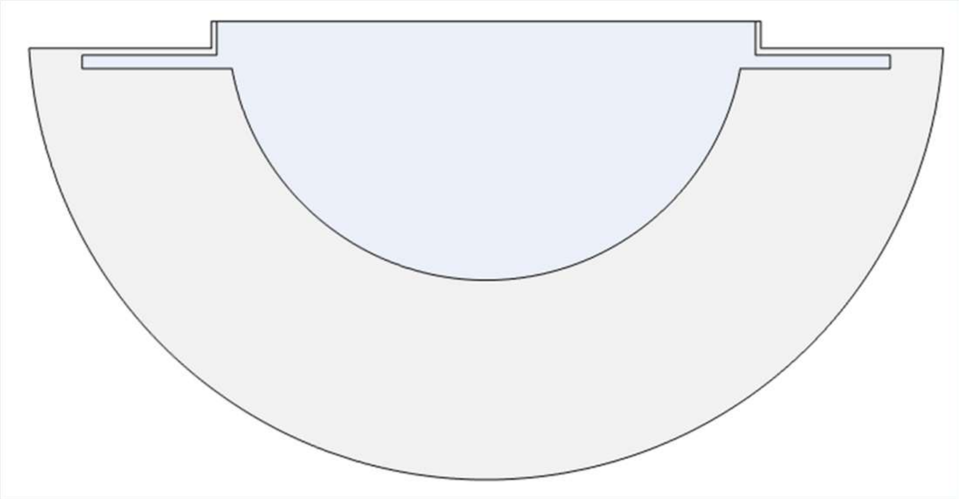


H_2 effects on transit time velocity measurement

- → Acoustic impedance
  - The very low density of hydrogen contributes to a low acoustic impedance
  - Effect on signal amplitude is a reduction by a factor of approximately 3 in hydrogen vs natural gas
- → Shorter transit time difference
  - Transit time difference is proportional to v/c^2
  - As SOS approx. 3 times higher than natural gas, transit time difference is approx. 9 times lower
  - Relative effect of noise is approx. 9 times higher



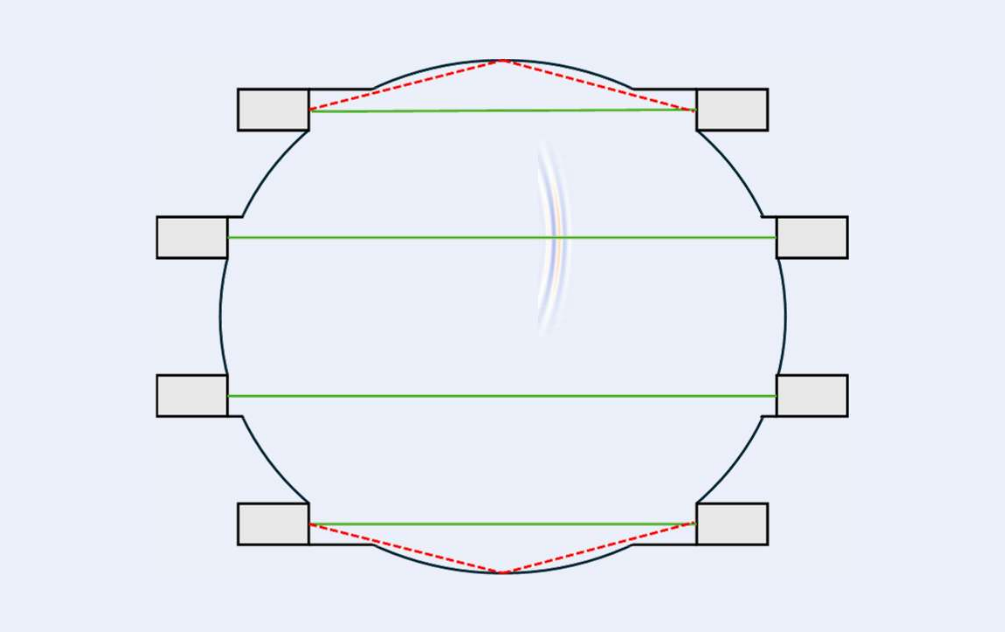
	Pressure transmission, transmit/receive across a planar boundary			
	Metal	Hydrocarbon oil	Methane 40 bar	Hydrogen 40 bar
Metal	100%	10%	0.11%	0.04%

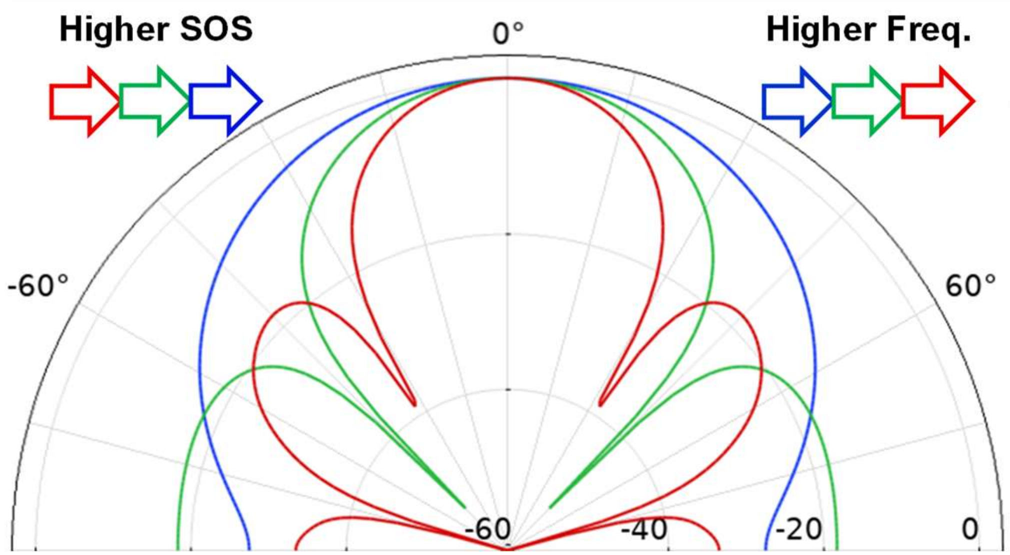


H_2 effects on transit time velocity measurement

→ Signal spreading

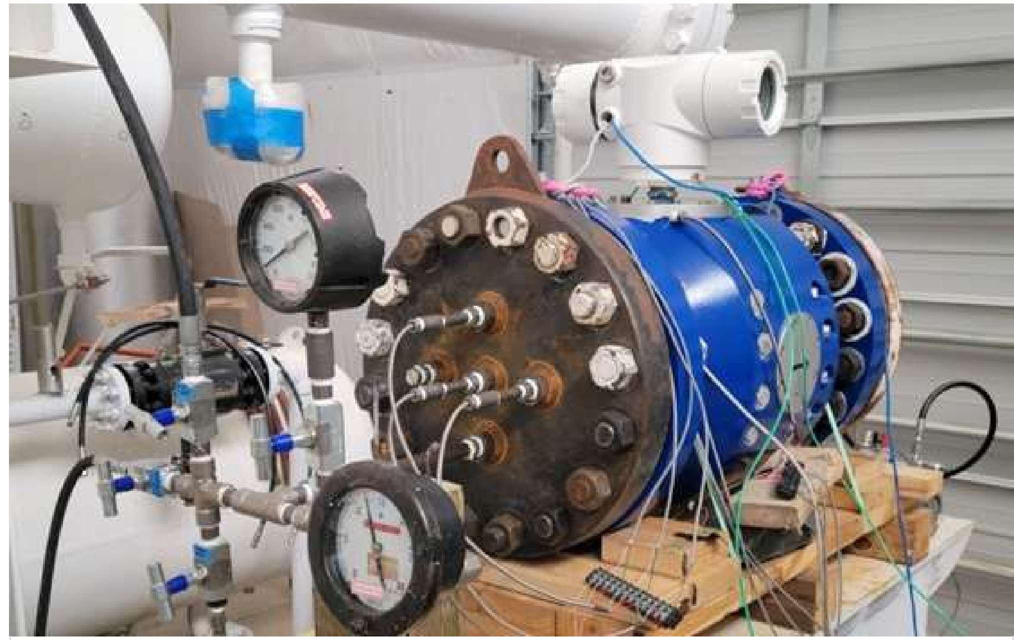
- The signal spreads out as it travels from transmitter to receiver
- The higher the sound speed or the lower the frequency, the more spread there is
- For H_2 versus natural gas, if the same frequency were used, this means increased signal loss, as the energy is spread over a wider area
- It also means that the received signal can potentially become corrupted by signals arriving via indirect paths (i.e. by reflection)

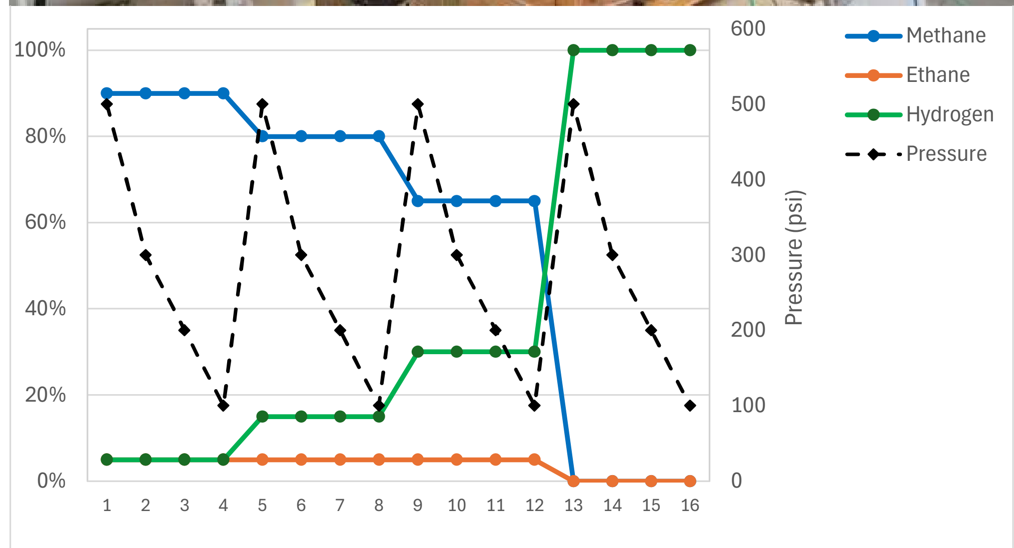




CEESI static test on standard gas meter

- Prior to starting our development project, we evaluated an 8-path Caldon 380Ci in static tests at CEESI with methane/propane mixtures with up to 30 % hydrogen, and with pure hydrogen
- Verified analytical modelling
- Confirmed the standard transducer performance is suitable for mixtures up to 30% hydrogen
- Confirmed significant improvements in transit time measurement uncertainty were required for high accuracy in pure hydrogen



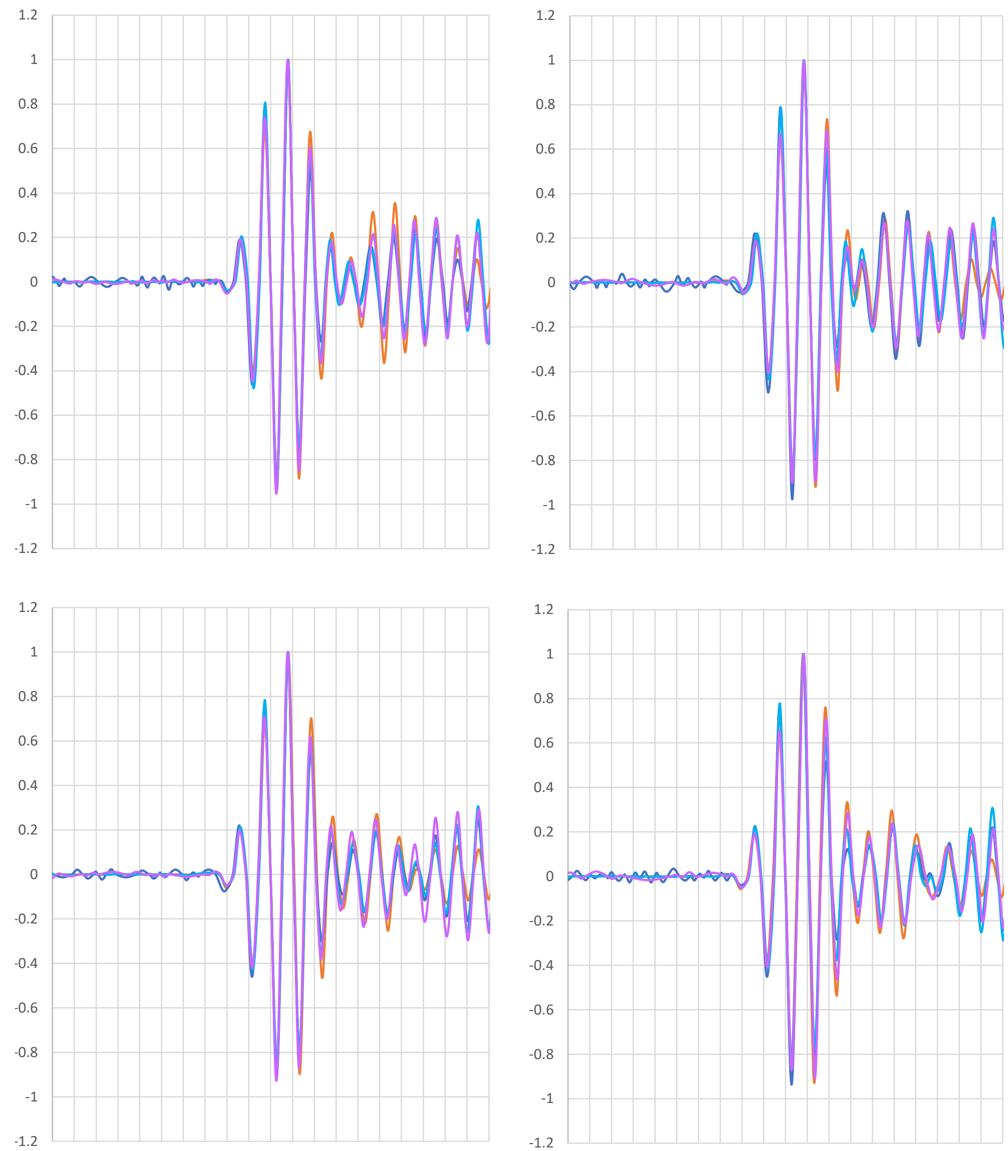


New transducers developed to meet the challenges of H_2

- → Decades of in-house experience in transducer design
  - Liquids and gases, high and low frequencies
  - Temperatures from cryogenic to > 450 °F (230 °C)
  - Line sizes from ¼"(chemical injection) to > 42"
- → Development for H_2
  - Improved signal transmission efficiency and reduced spreading loss
  - Improved isolation and reduced sensitivity to self-generated (coherent) noise

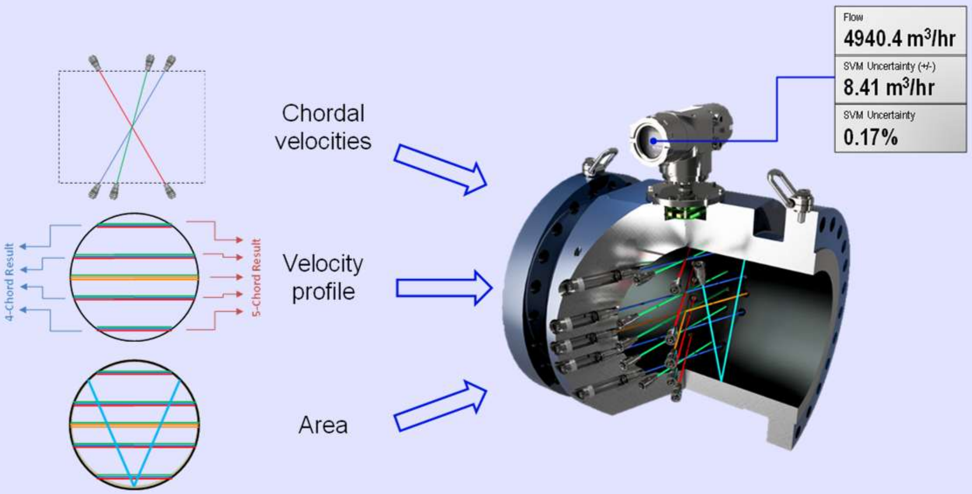
New transducers developed to meet the challenges of H_2

- → Transducers were characterized by static testing using air, liquid hydrocarbon, and nitrogen and helium at various pressures
- → These tests span a range of sound speed from approx. 1125 ft/s (343 m/s) to approx. 4600 ft/s (1400 m/s) with fluid density ranging from approx. 0.8 lb/ft^3 (1.2 kg/m^3) to approx. 50 lb/ft^3 (800 kg/m^3)
- → The graphs show single-waveform snapshots across these fluids on four transducer pairs, with excellent reproducibility of waveform shape



H_2 specifications and options

- → 200 ft/s (60 m/s) nominal max velocity
- → 2 ft/s (0.6 m/s) min velocity at 460 psi (32 bar)
  - Below 32 bar min velocity = 0.6 m/s * 32 bar / P
- → As the same field proven electronics are used for liquids and gases, hydrogen can be measured with meters in 4-path, 8-path or SVM format
- → The live uncertainty output feature of the SVM format provides quantitative verification of both
  1. Transfer of calibration from the lab to the field
  2. Operation in field service over time with process changes



Live evaluation of uncertainties

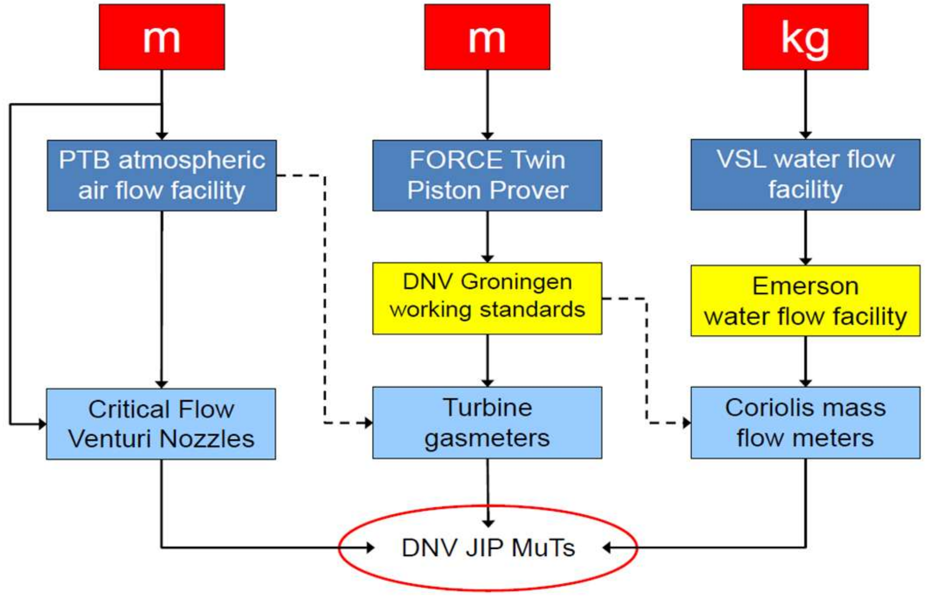
DNV H_2Met JIP objectives

- → To enable the industry to test and assess H_2 metering technologies
- → By establishing a traceable H_2 gas mixture test facility in which flow meters can be calibrated
- → And testing a range of different metering technologies to establish a good understanding of their performance and challenges when measuring gaseous H_2

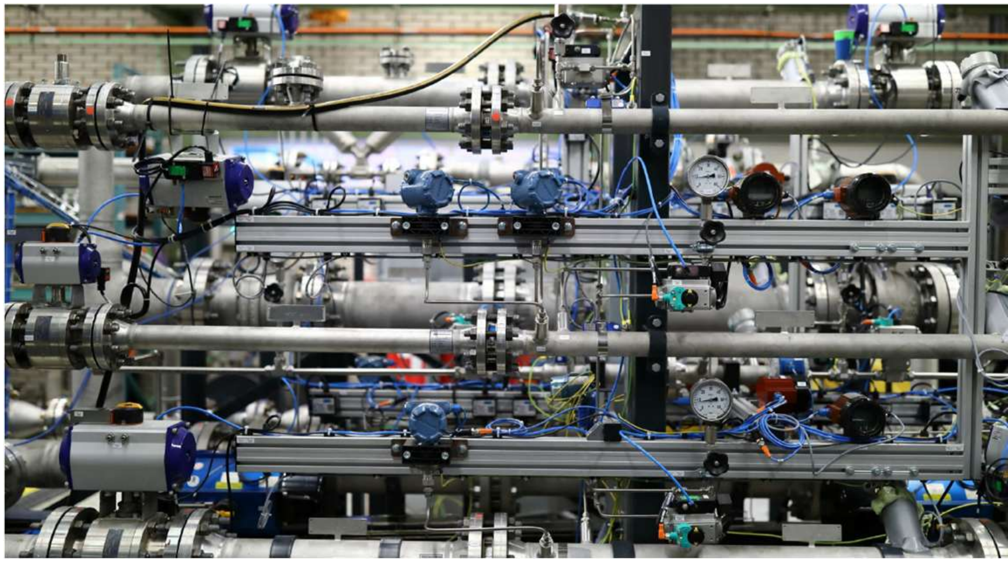
Project partners

- Aramco
- BP
- Equinor
- Gas Networks Ireland
- Gassco Norway
- Gasunie
- OQ Gas Networks
- Petrobras
- Petronas
- Shell
- Cignus
- Canalta
- Emerson
- Endress+Hauser
- Fluenta
- Krohne
- Siemens
- SLB (Sensia)
- Yokogawa

DNV reference system

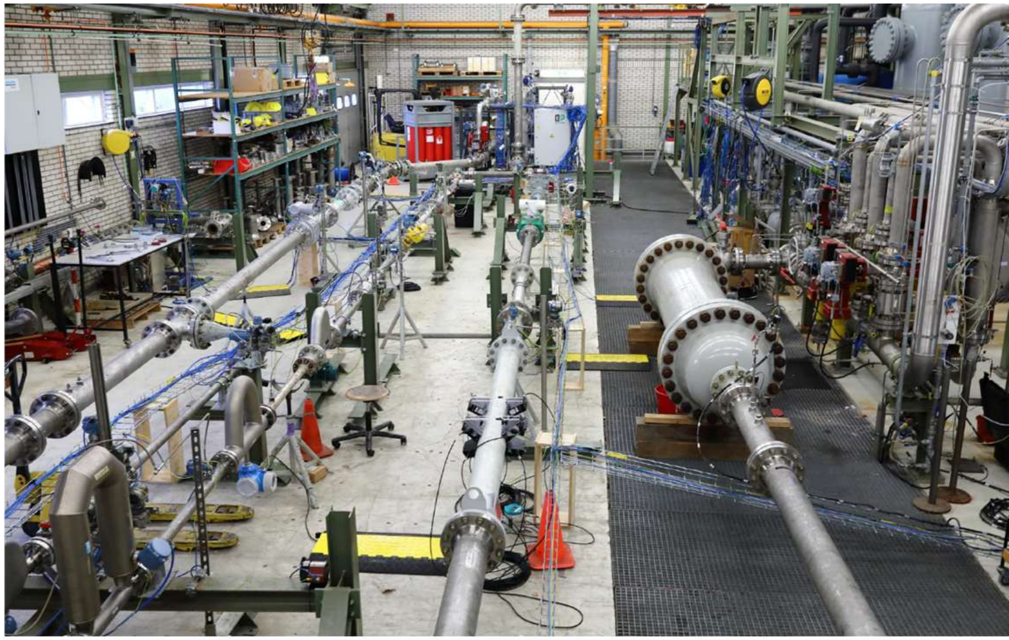


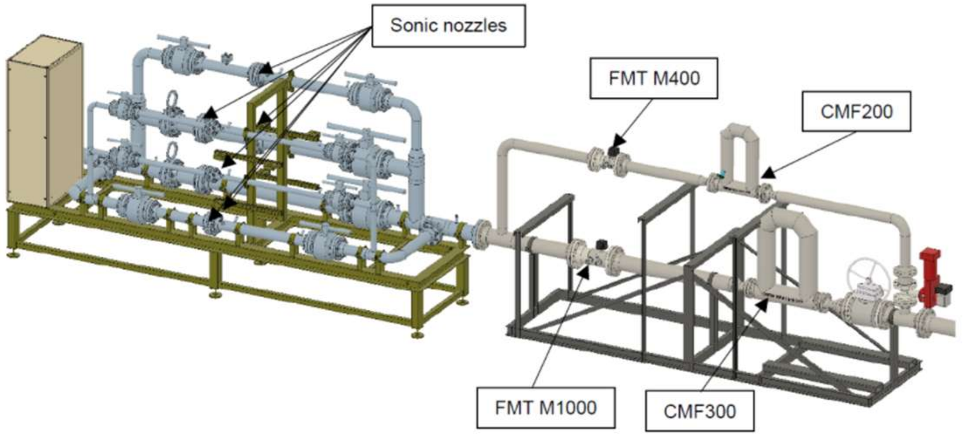
- → Reference gas **mass** flowrate derived by combining three distinct technologies (sonic nozzles, turbine and Coriolis) with separate traceability chains
  - Agreement ensures gas property effects on the reference meters has been managed within the expected uncertainty
- → Reference **density** inferred from composition, pressure, temperature and speed of sound
- → Combined uncertainty in reference volume flowrate typically between +/- 0.35 and +/- 0.4%



Test conditions

- → Blind test with no access to reference flowrates and no configuration adjustment
- → Three pressures: 8, 16 and 32 bar (a)
- → One temperature: ~20 °C (controlled ambient)
- → Four compositions: 99.9%, 99.5%, 98%, 95% H_2
  - – Contamination primarily methane and nitrogen but also water vapor and others
- → Flowrates from 16 to 763 m^3/hr
  - – Velocity in 4” from 2 ft/s to 94 ft/s (0.6 to 28.6 m/s)
- → Minimum eight flowrates per test
- → Reynolds numbers from 6,000 to 1,000,000





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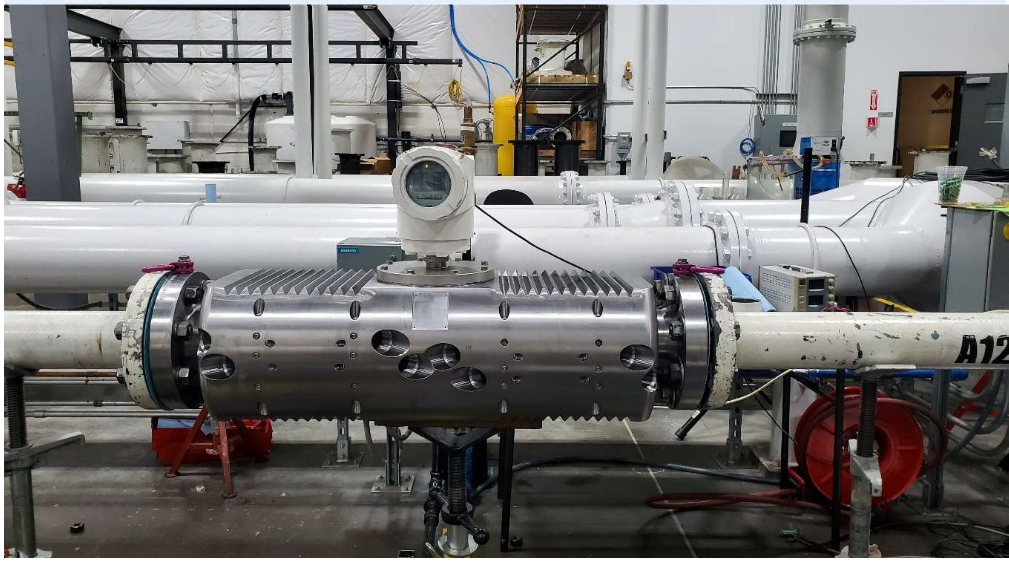
Meter selection and preparation

→ DNV test represents the most challenging H_2 conditions for an ultrasonic meter
  - USM performance improves when meters are larger, pressures are higher, velocities are higher, and Reynolds number is higher

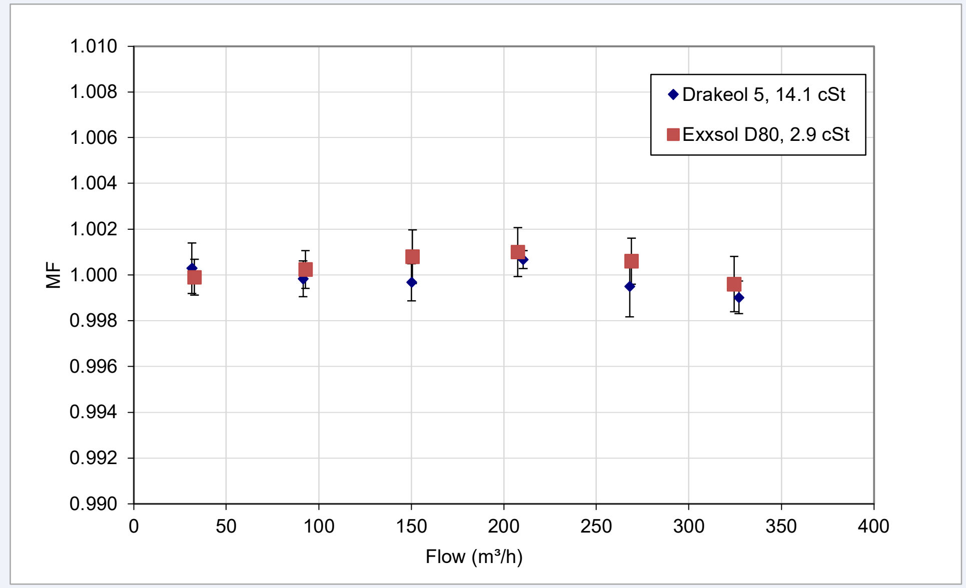
→ A 4-inch size and 8-path meter configuration was selected for the test
  - Elongated body required in the 4-inch size to accommodate 8 paths; this is not needed for 6” and larger

→ Owing to the low Reynolds numbers to be covered, viscosity was calculated as a function of P, T and SOS to enable Reynolds correction



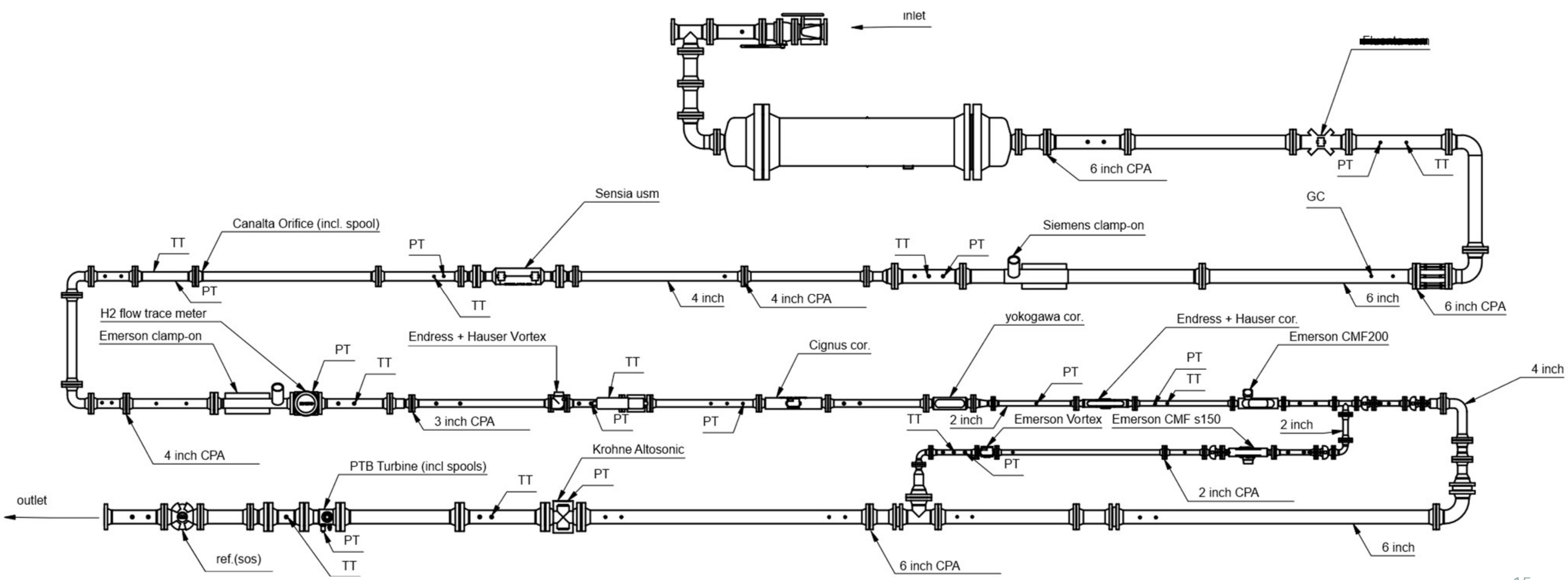
Factory calibration in liquid hydrocarbon

- Following consideration of available options, a baseline calibration was performed at the SLB CALDON Technology Centre using liquid hydrocarbons of approx. 3 and 14 cSt
- ISO 17025 accredited laboratory
- The labs SVP reference standard with accredited uncertainty of +/- 0.04 % was used
- Meter was calibrated over a Reynolds number range of approx. 8,000 to 140,000
- Calibration results within +/- 0.1%



DNV test line set-up

- → 5 x Coriolis (two 3”, three 2”)
- → 2 x Custody Transfer USM, (CALDON 4” and another 6”)
- → 2 x Clamp-on USM (4” and 6”)
- → 2 x Vortex (both 2”)
- → 1 x Orifice (4”)



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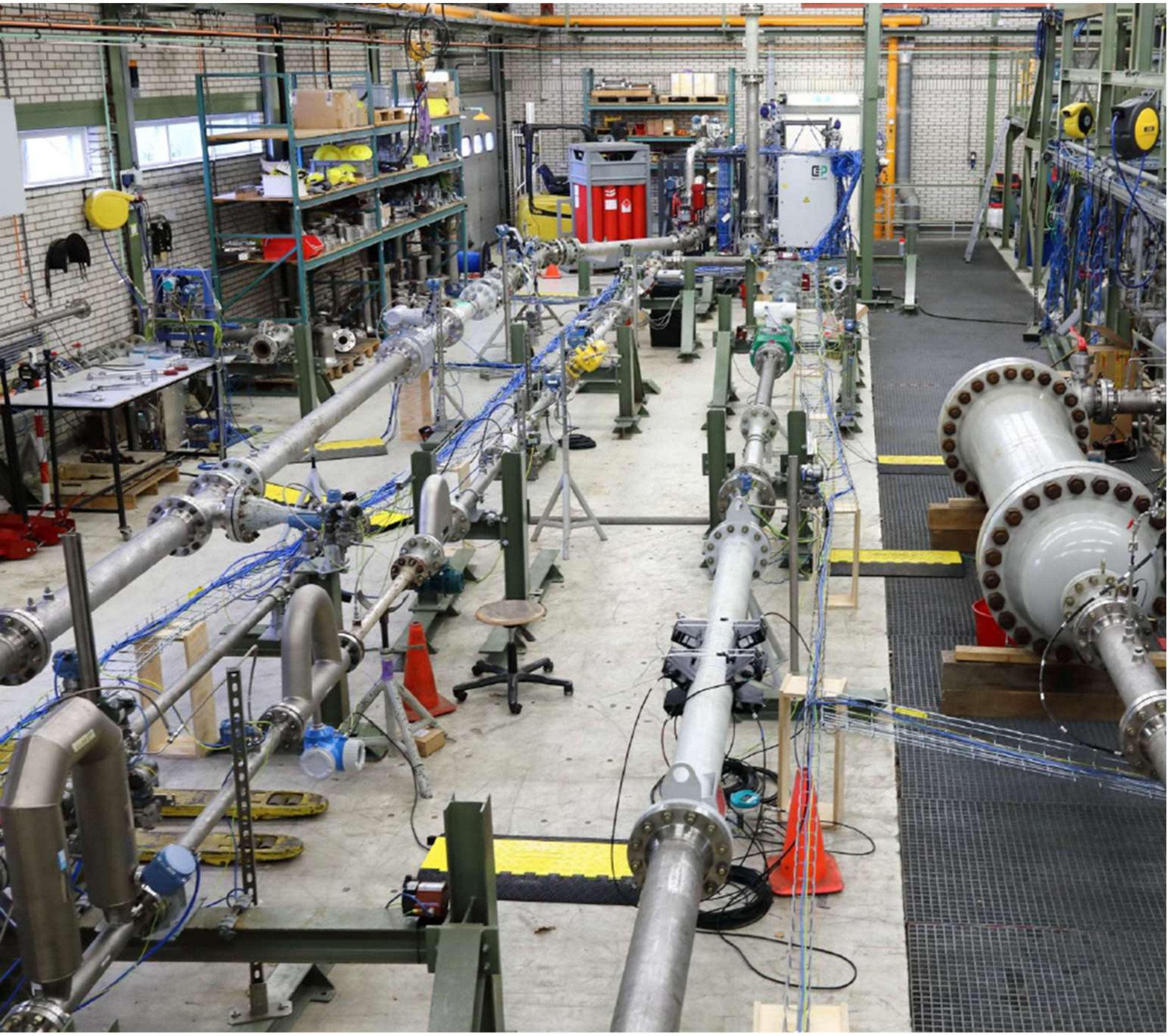
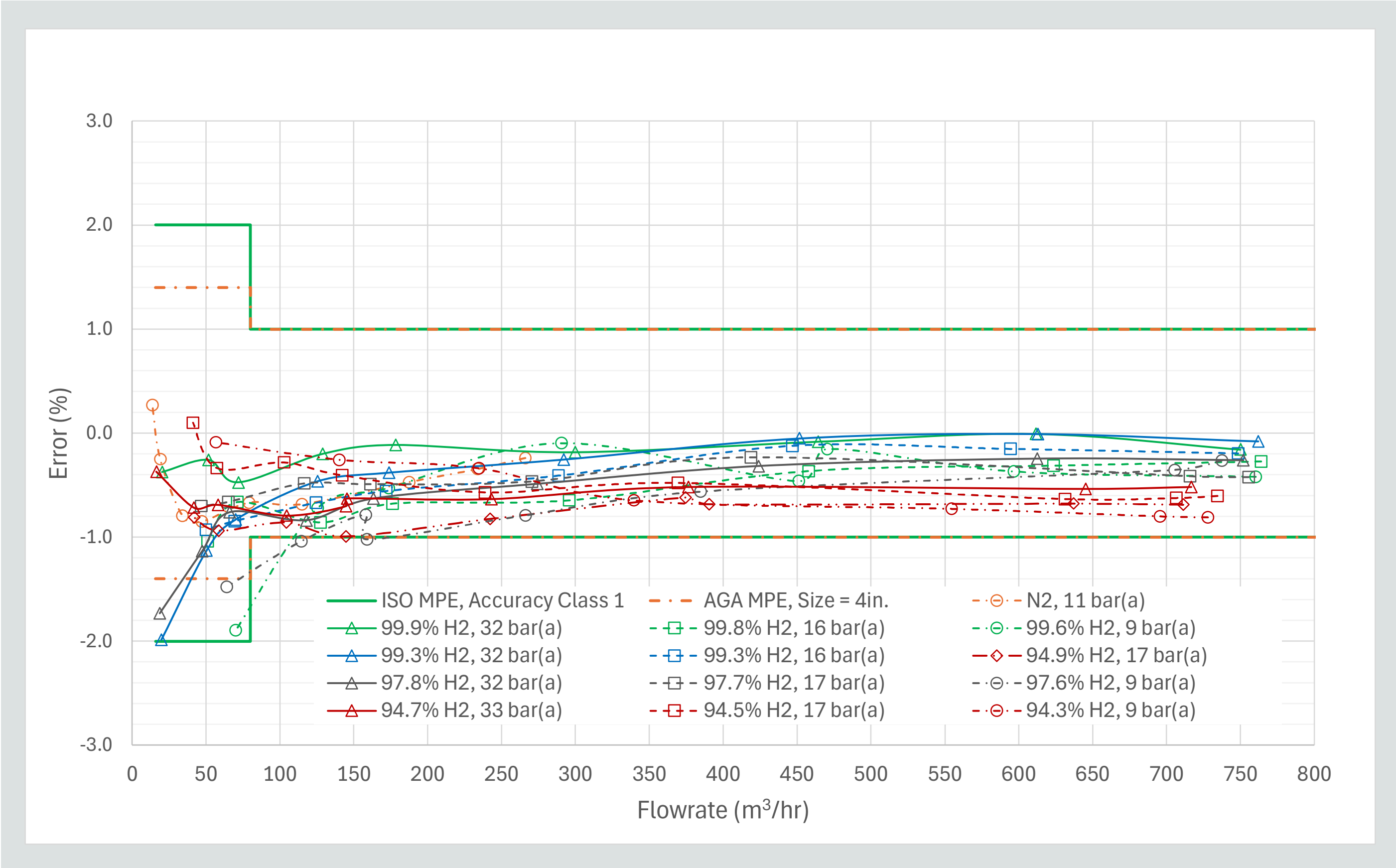


Test results

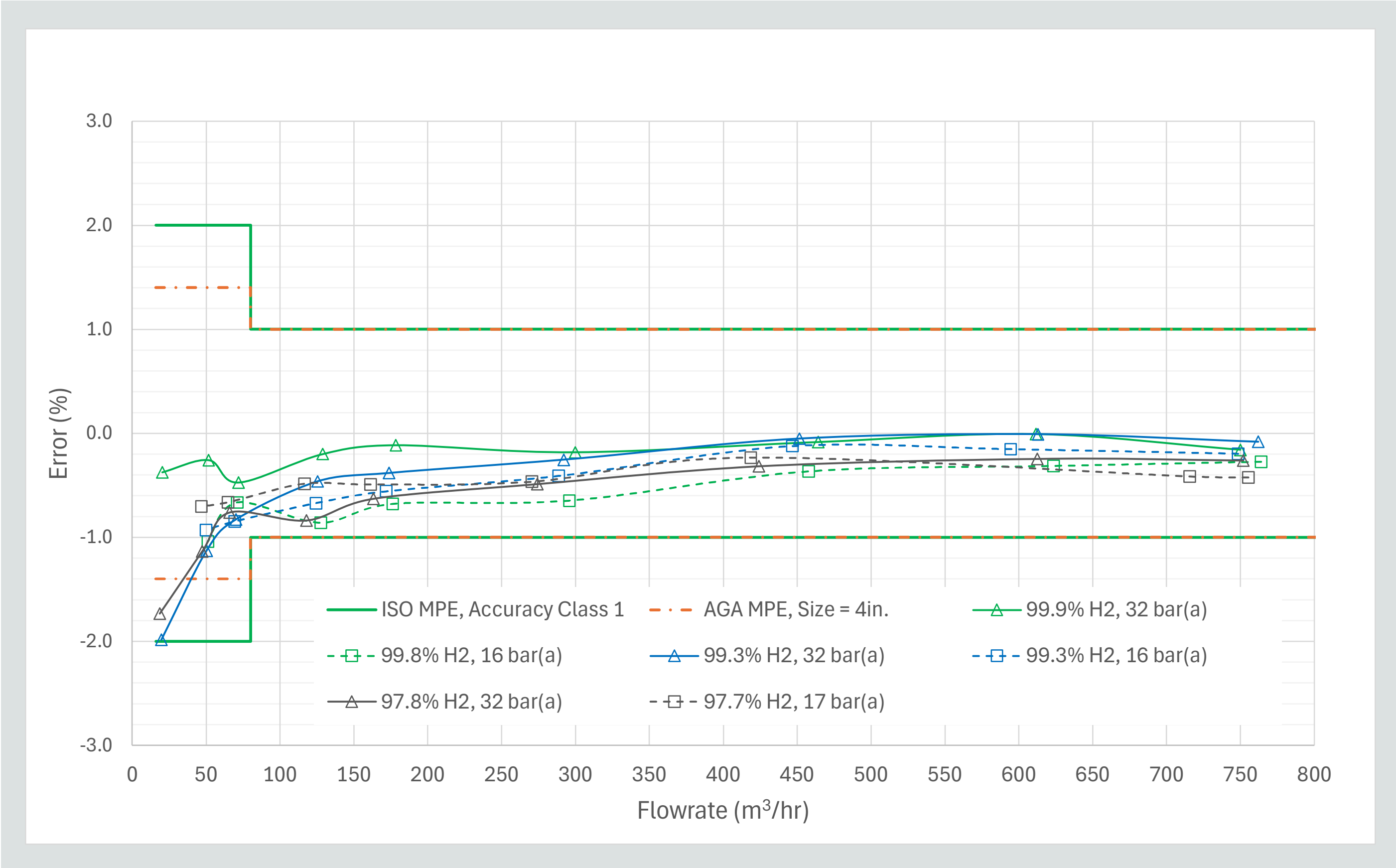
All results

- → No adjustments
- → All compositions from 94.3 to 99.9 % hydrogen
  - – Plus a nitrogen test
- → All pressures from 8 bar to 32 bar
- → Spread of results approximately +/- 0.4% over the majority of the flow range



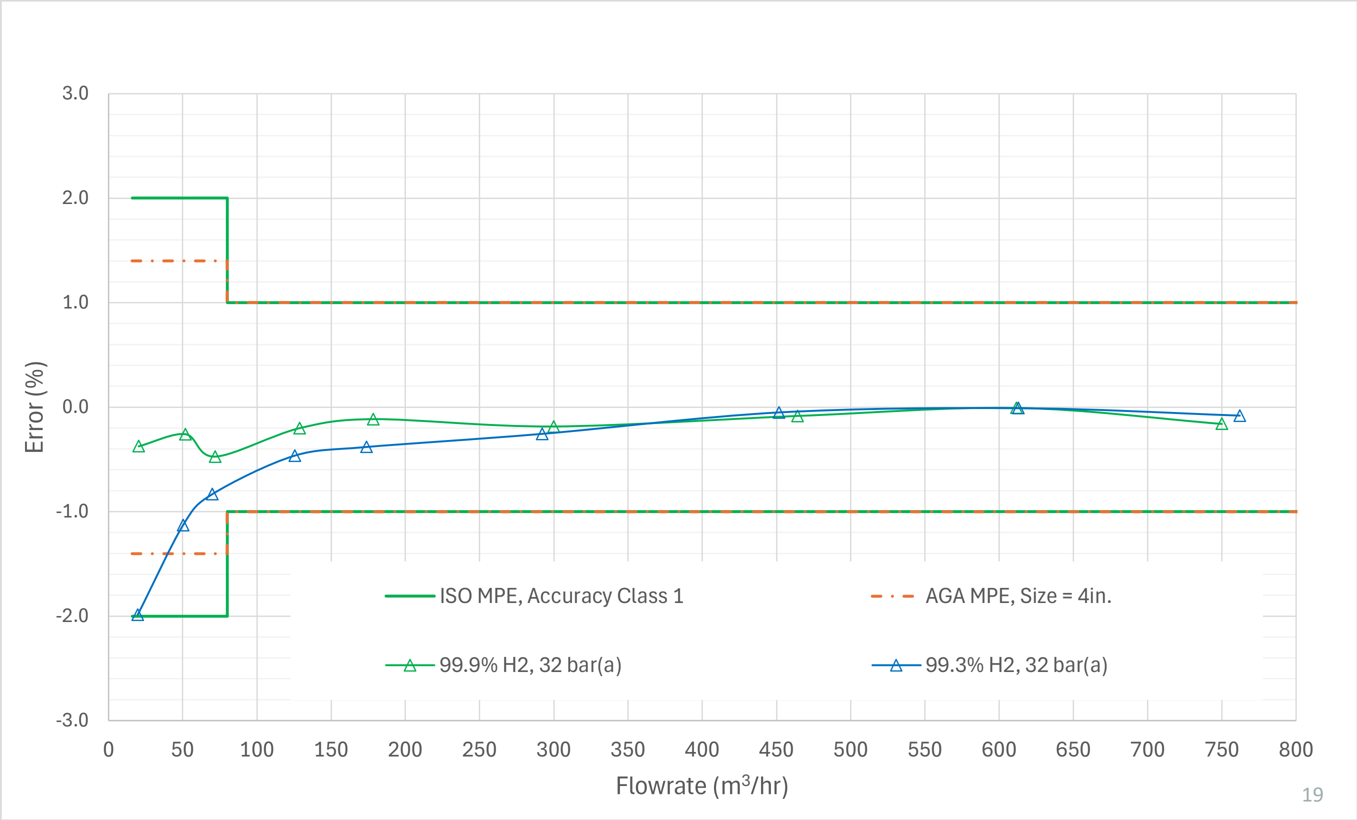
Purity ≥ 98%, pressure ≥ 16 bar

→ With the 95% purity and 8 bar pressure results removed the reproducibility at high flow is within a band of +/- 0.2%



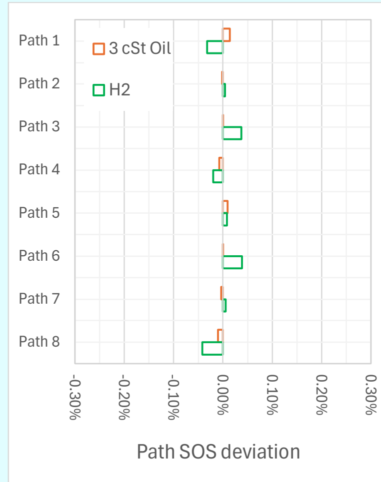
Purity ≥ 99%, pressure 32 bar

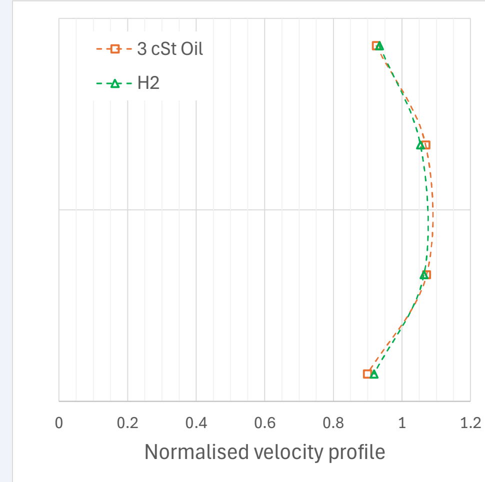
- → These are the most realistic conditions for high-capacity pipeline transportation
- → At high flows errors are less than +/- 0.25% with excellent reproducibility
- → Errors are within +/- 0.5% and reproducibility within +/-0.15% when velocity is above 10 ft/s (3 m/s)

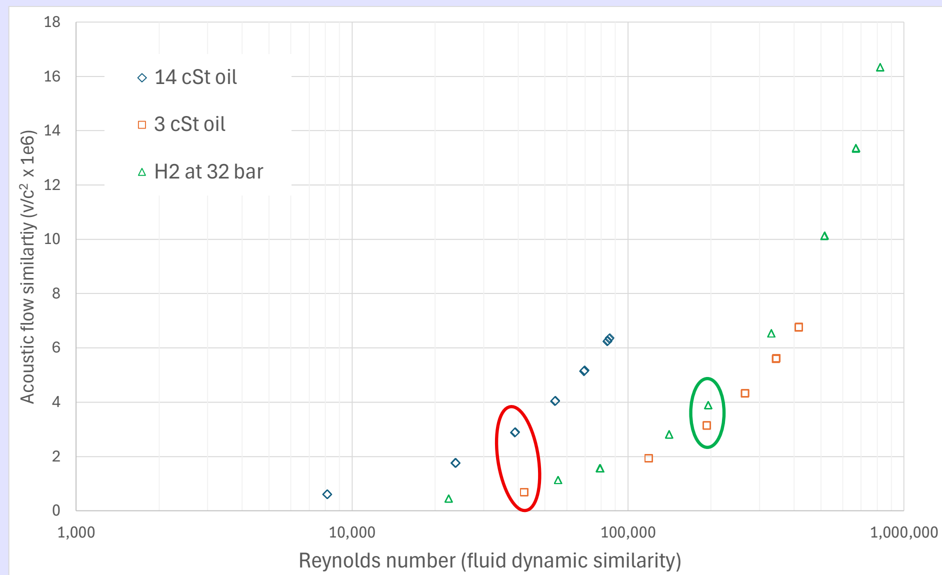


Dynamic and acoustic similarity of hydrogen and liquid hydrocarbons

- → The similarity of acoustic and dynamic conditions can be compared by plotting velocity over sound speed squared (v/c^2) versus Reynolds number
- → When this done using the data from the two oil tests performed before the JIP testing and the hydrogen data at 32 bar, there is in fact closer similarity between hydrogen and the 3 cSt oil than between the two oils



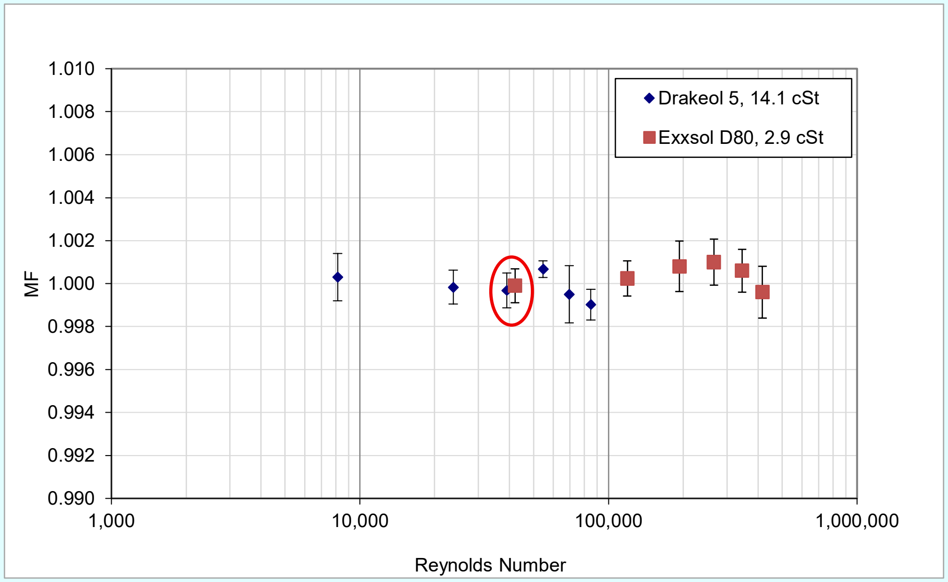


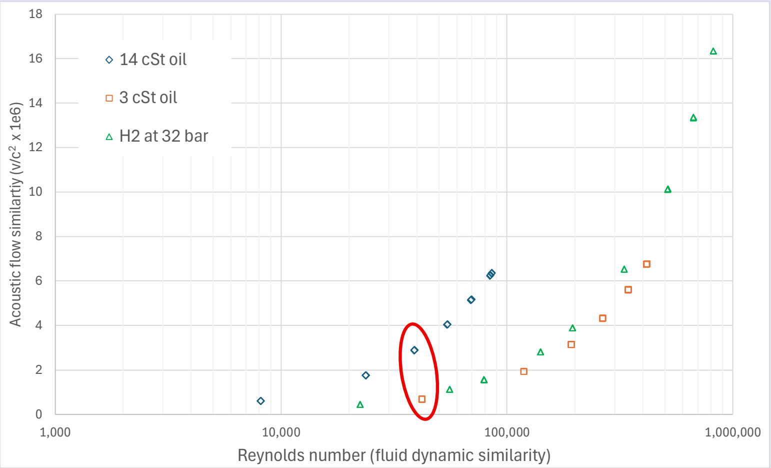


Dynamic and acoustic similarity of hydrogen and liquid hydrocarbons

→ At the conditions of greater dissimilarity between the two oil calibrations, the difference in meter factors/error between the two oils is only 0.02%

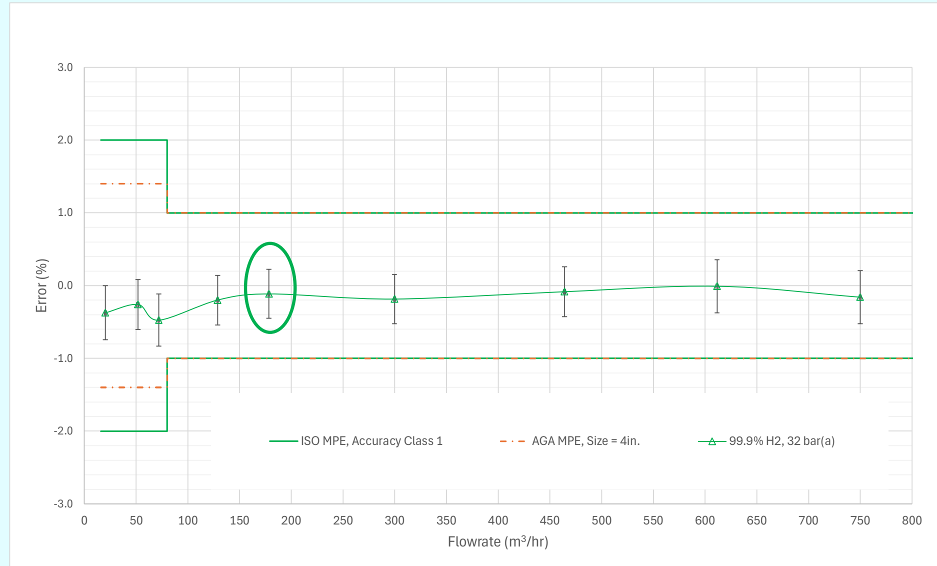
→ On this basis we would expect that the 3 cSt oil should transfer to hydrogen with very low uncertainty

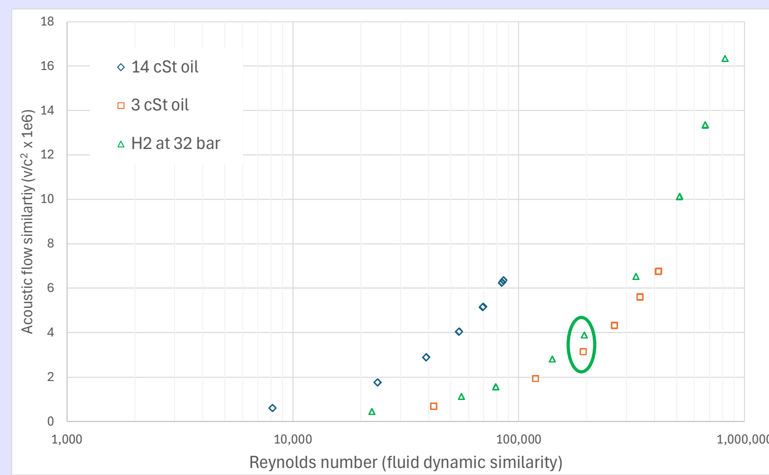




Dynamic and acoustic similarity of hydrogen and liquid hydrocarbons

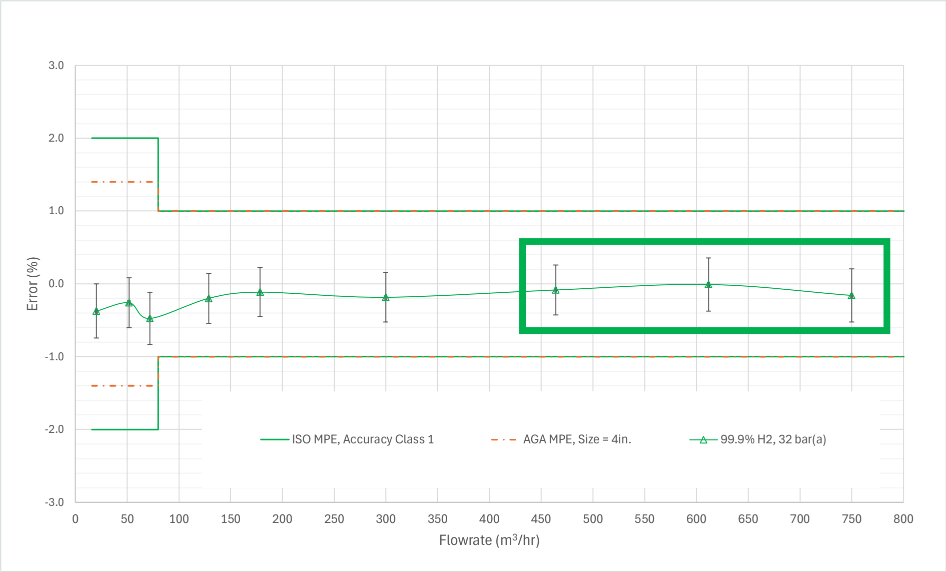
- When error bars equal to the DNV reference uncertainty are added to the hydrogen calibration points it can be observed that in all but one case the errors are within the uncertainty of the DNV facility
- In other words, these result demonstrate transferability of calibration from a fluid with density of approx. 800 kg/m3 to a fluid with density of approx. 2.7 kg/m3 (a ratio of approx. 300:1)

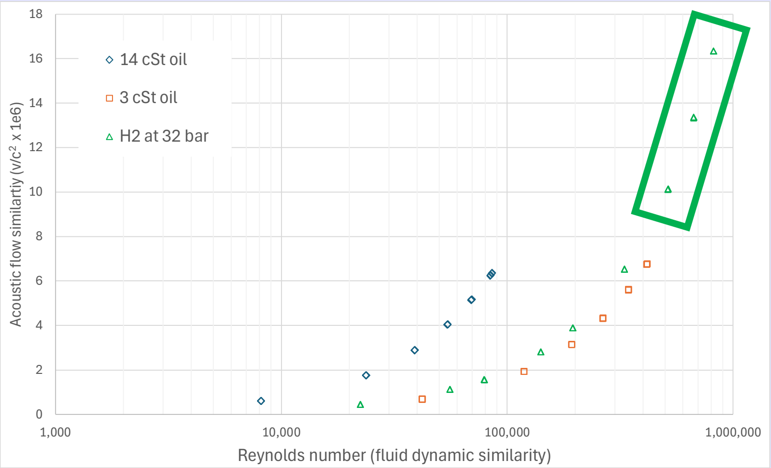




Extrapolation to Higher Reynolds numbers

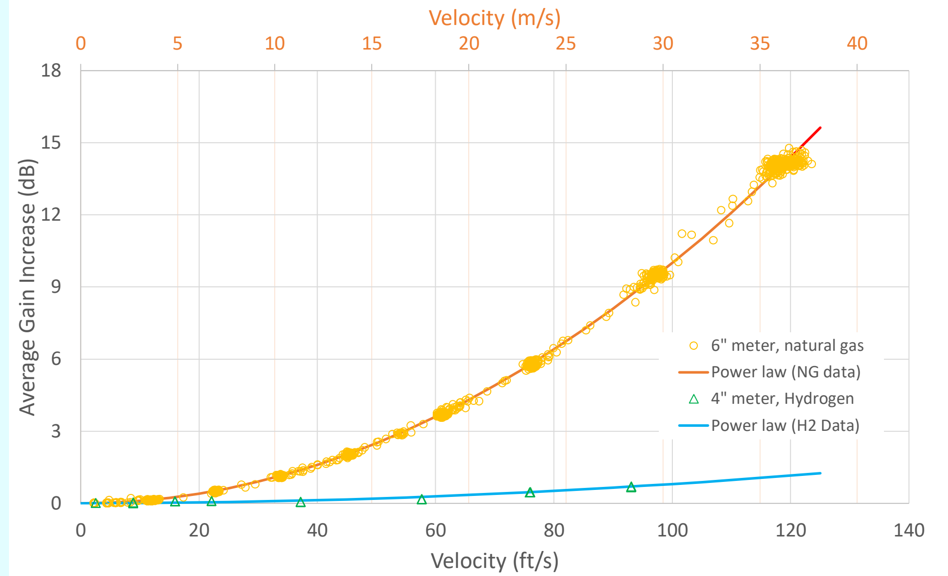
- Extrapolation of calibration to Reynolds numbers that are higher than those that can be achieved during calibration has an established practice for CALDON liquid meters in LNG and nuclear (high temperature water) applications for decades
- The results of the three maximum flowrates in hydrogen demonstrate low uncertainty in extrapolation to higher Reynolds numbers, where the oil calibration was limited to a max of approx. 140,000 Reynolds no. and the H_2 tests extent to > 800,000 Reynolds no.

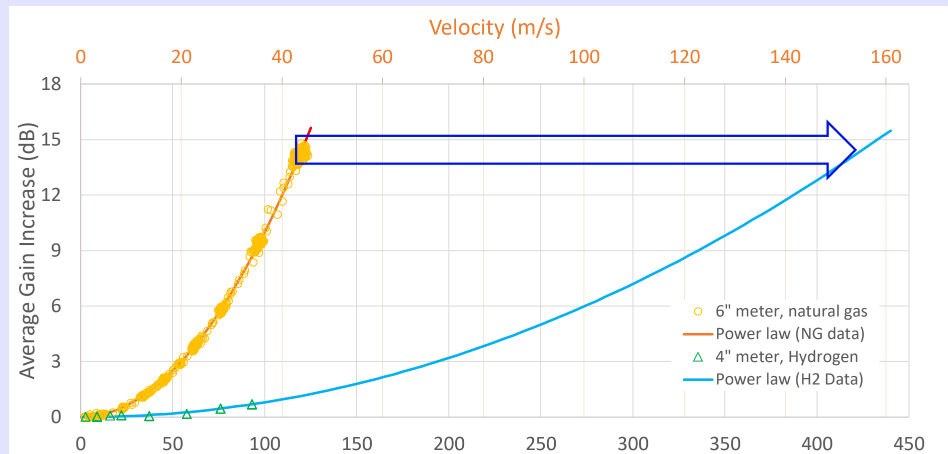




Maximum velocity limit in hydrogen vs natural gas

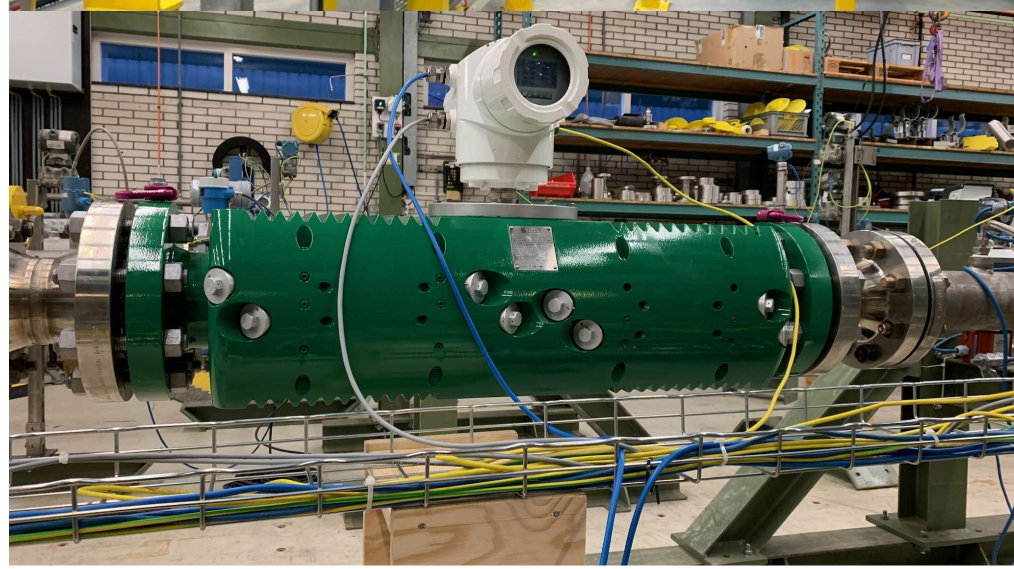
- → In natural gas ultrasonic meters are velocity-limited in owing to the relatively low sound speed of the fluid
- → Typical maximum velocities are 100 to 120 ft/s (30 to 36 m/s) in natural gas
- → Despite the DNV H_2 tests only extending to velocities of approx. 93 ft/s (28 m/s) the gain and SNR trends confirm that the meter could continue to operate accurately at much higher velocities





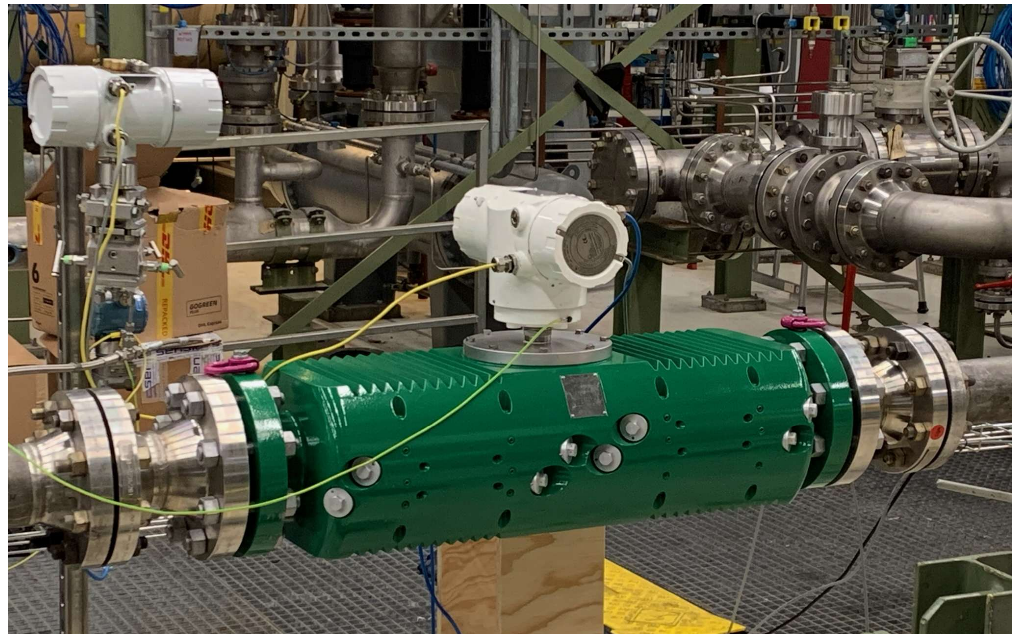
Liquid and supercritical CO_2

- The 4-inch meter is scheduled to be tested at the new TUV SUD National Engineering Laboratory liquid and supercritical CO_2 facility
- This is a small-scale facility with a maximum flow of 70 m^3/hr, limiting velocity of a maximum of around 8.6 ft/s (2.6 m/s)
- The meter will also be calibrated in the NEL water facility, resulting in a combined set of traceable calibration of this meter for water, 3 cSt oil, 14 cSt oil, nitrogen and four different hydrogen mixtures



Summary

- → Transducers have been developed for the CALDON product line to enable high accuracy metering of high purity hydrogen gas
- → Testing under the very demanding conditions of the DNV H_2Met JIP demonstrated custody transfer performance across all conditions
- → Low uncertainty transfer of calibration from liquid hydrocarbon to hydrogen gas over a density span of 300:1 was demonstrated
- → Above 10 ft/s errors were less than +/- 0.5 % at 32 bar for 99+ % pure H_2
- → Testing with additional fluids is planned, including liquid and supercritical CO_2



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- Canalta
- Emerson
- Endress+Hauser
- Fluenta
- Krohne
- Siemens
- SLB (Sensia)
- Yokogawa

DNV