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Technical Paper

Practical experience, Challenges and Solutions at Testing and Calibrating of Hydrogen Ultrasonic Flow Meters

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1 INTRODUCTION

Expansion of hydrogen infrastructure is going on at a rapid pace. Having seriously considered the use of hydrogen as an energy carrier about 5 years ago, the hydrogen community has been moving year by year towards the realization of this idea. Figure 1 shows a map with numerous hydrogen projects [1], dated December 2023, where the total number of projects in May 2023 and 2022 [2] are also shown retrospectively at the bottom. The number of projects has almost doubled in the period provided. Obviously, hydrogen infrastructure also requires accurate flow measurement technology.

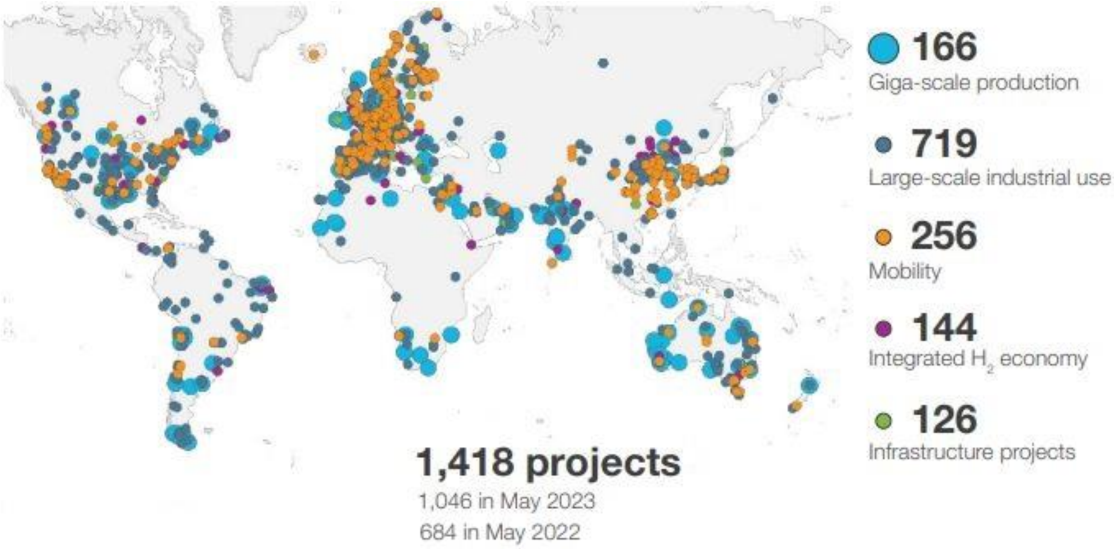

Figure 1. Hydrogen projects all around the world in December 2023 with retrospective total number of projects dated May 2023 and May 2022 at the bottom line (taken from [1,2]).

Ultrasonic flow meters (USM) have long proven to be the preferred solution for fiscal natural gas flow measurement and their use is well documented, for example in ISO 17089-1 [3], but new challenges arise when adapting these meters for hydrogen, both on the part of the manufacturer and the calibration infrastructure.

Despite this, the first recommendations for hydrogen gas measurement published by DVGW Gas No. 32 [4] recommends the use of ultrasonic instruments as master meters, but only with a serial connection between USM and another technology until an accredited test bench is available.

This paper presents the ultrasonic meter manufacturer's perspective on the challenges and solutions during practical experiments at production testing and high-pressure calibration.

Among the changing calibration standards and techniques, we explore the complexities of adjusting these meters, along with their production and testing methods, to accommodate the unique characteristics of hydrogen.

2 ULTRASONIC GAS FLOWMETERS FOR HYDROGEN PIPELINES

After conducting a preliminary analysis of hydrogen's properties and anticipating the initial challenges (such as acoustic interference from signal reflection off pipe walls and the need for greater accuracy and reproducibility in time difference measurements), SICK chose to develop a brand-new ultrasonic meter for Custody Transfer Hydrogen gas measurement – the FLOWSIC610. Figure 2 illustrates the extensive process from concept to final product.

Figure 2. Journey from concept to final product

The newly developed hydrogen USM has all the standard advantages of the technology:

- No pressure loss
- High measuring range ≥ 100:1
- No mechanically moving parts
- Low flow and low pressure capability
- Wide range of nominal diameters starting from DN50
- Continuous meter health monitoring and diagnostics

In addition to these known technology advantages, it offers new benefits:

- Capability for high flow rate / velocity (three times that of natural gas) to enable equivalent energy transportation
- Hydrogen purity determination via speed of sound (SOS)

Along with specially designed transducers and electronics, the production testing procedures were also adjusted to minimize uncertainty. For instance, the dry calibration process (including zero point testing and SOS adjustment) has been optimized. Further details provided in the next chapter.

3 STATIC TESTS: EXAMPLE OF SPEED OF SOUND ADJUSTMENT

To determine the flow velocity (VOG) through an ultrasonic meter, the geometric parameters (path length L and path angle α), the transit times $t_{AB/BA}$ of ultrasonic signals in both directions, and their transit time difference Δt are required, as shown in formula (1).

$$\mathrm{VOG} = \frac{L}{2 \cdot cos\alpha} \cdot \frac{\Delta t}{t_{AB} \cdot t_{BA}} \qquad (1)$$

To achieve the lowest possible overall uncertainty, it is crucial to minimize the uncertainty contributions from these influencing factors. Thus, in addition to geometric measurements performed at the factory, ultrasonic meters typically pass a zero-point correction. This correction reduces the uncertainty in time measurements by using a reference medium with a known speed of sound.

For natural gas meters, air is commonly used as the reference medium. However, using just air to calibrate a hydrogen meter can bring in additional uncertainty, due to the significant difference between the speed of sound in air (around 340 m/s) and in hydrogen (around 1300 m/s).

SICK has conducted a series of tests with different test gases and their combinations, the results of which can be found in the article "Testing and Calibration Problems of Hydrogen Gas Meters [5].

The best effect for applications where hydrogen as well as natural gas must be measured, is achieved by combining two different test gases covering the large range of SOS. Figure 3 shows a comparison of the uncertainties after zero-point adjustment of 3 different meters using the classical method with air versus adjustment with two test gases (for instance air and helium).

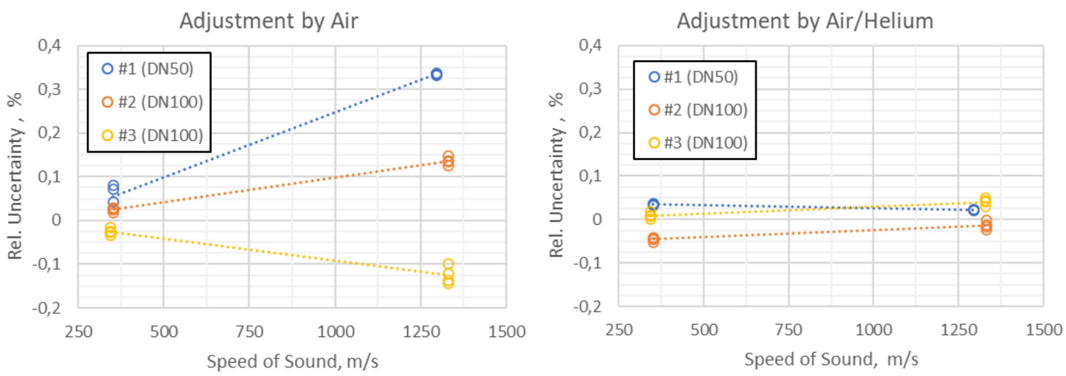

Figure 3. Tests results of relative uncertainty after zero flow adjustment with air (left)compared to adjustment with air & helium (right)

The initial uncertainty after zero flow adjustment with air, as shown in the graph on the left, can be significantly reduced down to ±0.05%, as shown in the graph on the right, by using two test gases.

4 ENSURING EQUIVALENT ENERGY TRANSPORTATION CAPACITY

To meet the goals of the Paris Agreement, a large expansion of hydrogen infrastructure is essential. Various studies have shown that repurposing the existing natural gas network can save more than 75% of the costs compared to building new infrastructure. According to a DNV white paper [6], this cost saving potential will result in more than 50% of hydrogen pipelines worldwide being converted from natural gas pipelines, with the figure reaching up to 80% in regions with well-established natural gas networks.

Considering the following factors:

- Hydrogen has a density approximately nine times lower than that of natural gas,
- The gravimetric heat of H2 combustion is three times greater than that of natural gas,
- Repurposed gas pipelines cannot accommodate increased design pressure or size,

many studies conclude that to ensure equivalent energy transportation capacity, the operational flow volume at the same pressure will need to be 2.5 to 3 times higher than in the existing natural gas networks [6,7].

The ability to detect high flow velocities presents a significant challenge for manufacturers, but once this capability was developed, it became a distinguishing feature of the FLOWSIC610. To meet this requirement, the design of the ultrasonic flow meter must consider the following acoustic effects:

Flow noise: Flow noise is a key factor that can impact the accuracy of measurements, as the noise generated should not override the signal. To estimate the impact of flow noise in hydrogen, the VDI 3733 standard "Noise in Pipelines" [8] can be used. This standard provides equations to calculate the sound power within a pipe, from which the expected noise sound power P can be derived:

$$P \sim \rho \cdot \frac{VOG^6}{SOS^3} \qquad (2)$$

When comparing hydrogen to natural gas, this leads to the conclusion that the same noise power P in hydrogen occurs at approximately 2.5 times higher velocities than in natural gas. Experimental evaluations under real conditions are ongoing.

Beam drift effect: The beam drift effect is another factor that limits the maximum flow velocity in a USM. This occurs when the flow profile inside the meter deflects the acoustic beam, causing only part of the signal to reach the receiver. The severity of this effect depends on the ratio of the gas velocity in the meter to the speed of sound, typically expressed as the Mach number:

$$\mathrm{Ma} = \frac{VOG}{SOS} \qquad (3)$$

For a fixed transducer design, beam drift in hydrogen will occur in the same range as in air but at velocities approximately four times higher than air and about three times higher than natural gas. Figure 4 illustrates the drift angle as a function of the Mach number and shows approximate velocities of air and hydrogen at identical Mach numbers. Theoretical calculations suggest that the maximum achievable flow velocity is greater than 75 m/s, and further tests are ongoing to confirm these results.

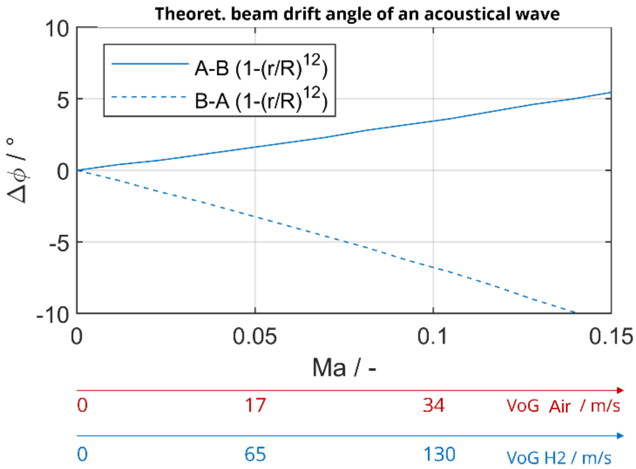

Figure 4. Drift angle depending of Mach number and approximate velocities of air and hydrogen

It is evident that the underlying physics allows higher gas velocities with hydrogen in ultrasonic flow meters due to the different properties of the medium.

To validate the theoretical assumptions, a series of experiments were conducted in the RMA calibration laboratory using 100% hydrogen. A DN100 meter was tested at pressures of 16 and 36 bar, with flow rates ranging from 7 to 2020 m³/h, corresponding to velocities between 0.3 and 80 m/s. The test results shown in Figure 5.

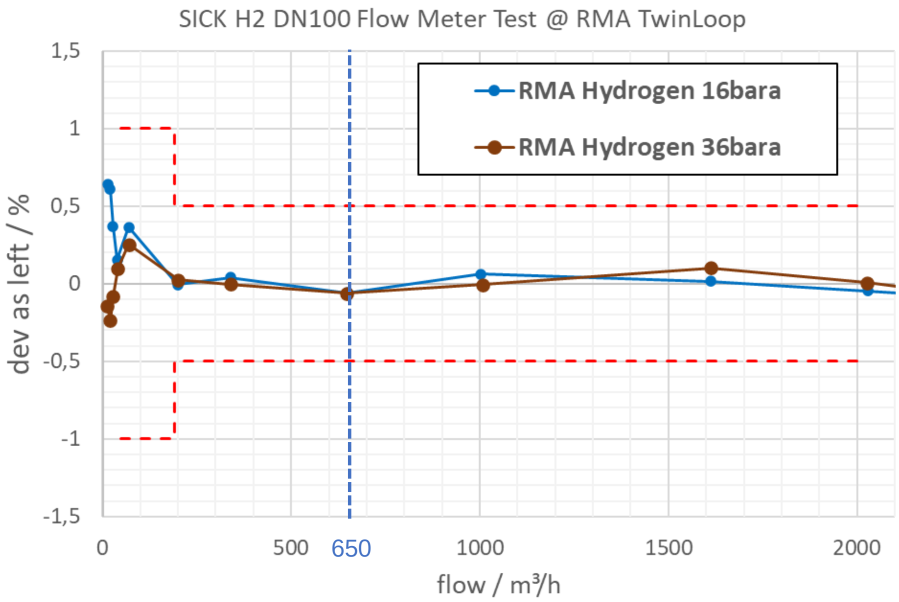

Figure 5. Uncertainty of the measurement for DN100 USM meter at RMA H2 test facility

As shown in the graph, the measurement uncertainty remains below 0.1% over the primary range of the meter, from Q_t to Q_{max}, with a turndown ratio of 1:100. Additionally, the test results showed no pressure dependence, as even at a relatively low pressure of 16 bar, the relative deviation (indicating repeatability) was less than 0.05%. The meter also performed reliably at high flow velocities, reaching up to 80 m/s without issues. To better illustrate the results, an additional blue vertical line has been added showing the typical Q_{max} of 650m3/h (~25m/s) for natural gas flow meters.

For flow velocities at and above 80 m/s, the first signs of flow noise were detected. Figure 6 illustrates the normalized flow noise levels at two different pressures, showing that the noise effect scales with both pressure and velocity as expected. However, these noise levels did not impact the meter's performance.

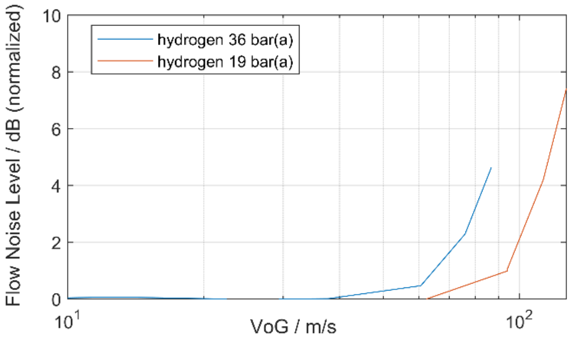

Figure 6. Observed normalized Flow Noise Levels during hydrogen flow tests with a DN100 flow meter

While further increasing the FLOWSIC610's maximum permissible flow rate is possible, there are currently no indications of gas velocities exceeding 80 m/s in gas transportation applications.

5 FLOW CALIBRATION WITH DIFFERENT TEST GASES

In March 2024, Dr. Eric Starke, in his article "Testing and Calibration Challenges of Hydrogen Gas Meters," provided a comprehensive analysis of the key factors impacting the calibration of both hydrogen and alternative gases. He concluded that hydrogen ultrasonic flow meters can easily achieve the expected measurement uncertainty after hydrogen calibration. However, current calibration capabilities are quite limited, raising the question of whether calibration with different test gases than Hydrogen is feasible. Initial investigations have shown that this is possible if the calibration is conducted at multiple pressures to cover the Reynolds number range, as illustrated in Figure 7.

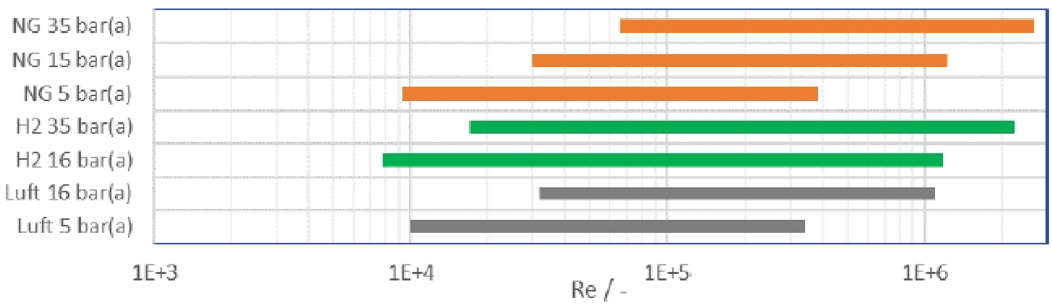

Figure 7. Reynolds number ranges for an exemplary hydrogen USM DN100 for different medium and pressures

As illustrated in the graph, choosing two different natural gas pressures or a combination of natural gas and air effectively covers the Reynolds number range relevant for hydrogen applications.

The first practical results of the DNV HyFLG test bench using an alternative test gas (natural gas at two different pressures) and their comparison with the DNV hydrogen bench calibration were also provided. The results are shown in Figure 8 and indicate a shift of the natural gas characteristic curve by about 0.6 % for the DN100 4-path test device.

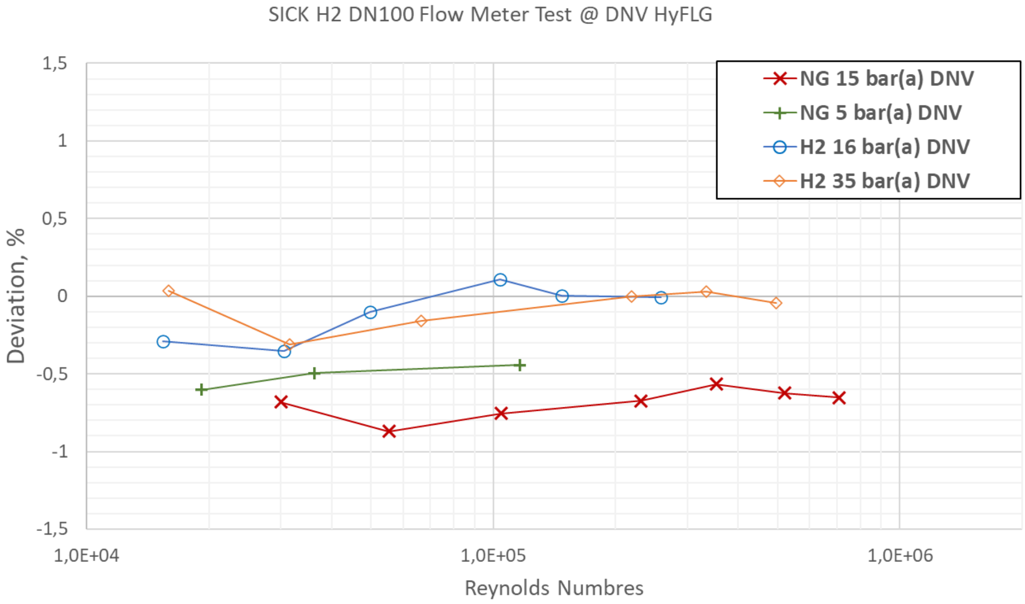

Figure 8. First results of hydrogen (H2) and natural gas (NG) measurements at the valid DNV test bench

Despite the test lab uncertainty of ±0.3% in the main range (or ±0.5% at low Reynolds numbers) and the experimental nature of the setup, the initial results regarding the transferability were promising. However, further testing is required to verify the applicability of natural gas calibration for hydrogen applications.

Figure 5 presents the results of testing the FLOWSIC610 on the hydrogen RMA calibration bench at pressures of 16 and 36 bar. Additionally, the same meter was tested on the natural gas RMA bench, with results shown in Figure 9.

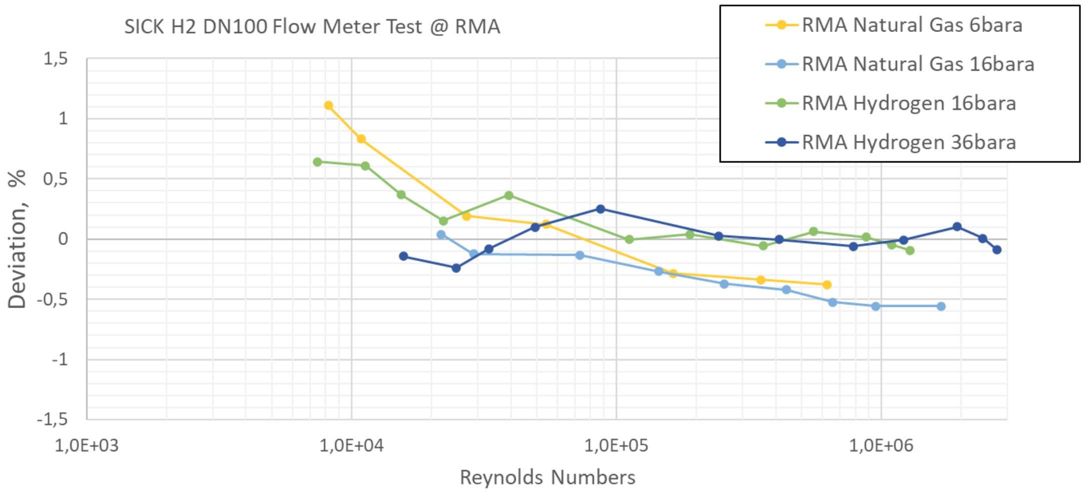

Figure 9. Results of hydrogen (H2) and natural gas (NG) measurements at the current RMA test bench.

The graph indicates that on the RMA bench, the DN100 USM shows an approximate shift of 0.3% between natural gas and hydrogen for Reynolds numbers above 20,000. That corresponds to a flow rate of about 20 m³/h or a gas velocity of 0.7 m/s. The maximum Reynolds numbers reached 2,700,000, which corresponds to flow rates exceeding 2,000 m³/h or velocity greater than 80 m/s, as depicted in Figure 5.

Figure 10 displays a combined graph showing deviations at the RMA and DNV test stands, with tests conducted using two different media (hydrogen and natural gas) at various pressures.

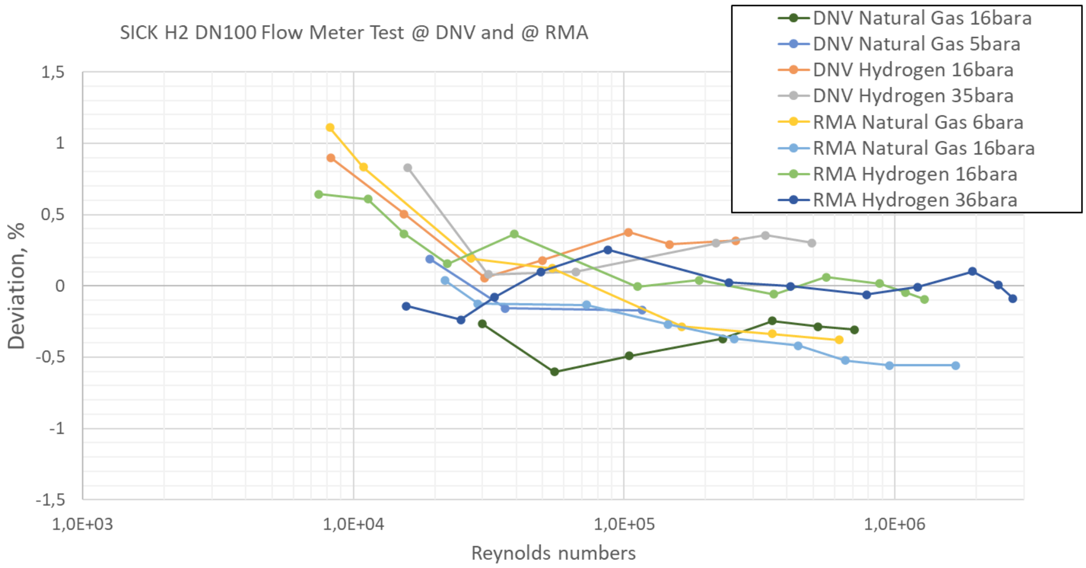

Figure 10 Combined test data from DNV and RMA for hydrogen (H2) and natural gas (NG) at different pressures.

Despite one hydrogen test stand not yet being accredited and the other being experimental, the transferability results fall within a ±0.5% range for both hydrogen and natural gas across a broad range of Reynolds numbers (10,000 to over 2,000,000 Re).

The test results for hydrogen are represented in the upper part of the combined graph, showing a deviation of approximately 0.3% for Reynolds numbers greater than 40,000. In contrast, the results for natural gas are concentrated in the lower part of the graph.

Of the four test graphs (RMA at 6 and 16 bar, and DNV at 5 bar), three show deviations of around 0.2%, while only the DNV test at 16 bar shows a deviation of 0.5% for Reynolds numbers below 200,000. SICK and DNV are continuing to analyze the testing data to identify the cause of this deviation, which is related to the calibration range of the reference equipment.

6 CONCLUSIONS

Ultrasonic meters are highly advantageous for hydrogen transportation networks due to their lack of pressure loss, a wide measurement range, low operating pressures requirements, and the continuous health monitoring through diagnostics. Their excellent measurement capabilities have been validated through several flow tests with hydrogen at various H2 test facilities.

Hydrogen's media properties differ significantly from those of conventional test gases, presenting challenges during both static tests and production. It has been demonstrated that helium can serve as an effective secondary test gas in Zero Flow tests to ensure deviations of less than 0.05% across a broad range of sound speeds in the gases.

The use of advanced transducers and electronics, combined with optimized production steps, enables stable performance at high flow velocity (up to 80 m/s), solving the challenge of an equivalent energy transport during infrastructure transformation.

While hydrogen ultrasonic meters achieve the expected measurement uncertainty after hydrogen calibration, the limited availability of test benches poses a challenge. This affects both flow tests for the type examination procedure and device calibration, raising the question of whether different test gases can be used for test and calibration. Flow tests conducted at various calibration facilities offer hope that the community's investigations are progressing in the right direction.

Tests with hydrogen and natural gas across different facilities have shown promising results. Deviations among eight different error curves are within ±0.5%. SICK, together with RMA and DNV test facilities, is continuing efforts to further optimize the deviation between hydrogen and natural gas results, paving the way for conducting tests at natural gas facilities with subsequent use in 100% hydrogen networks.

7 REFERENCES.

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