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Upgrading VSL's high-pressure gas flow primary standard for gases of the energy transition

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ABSTRACT

With the rise of Europe's sustainable economy, dedicated gas networks for carbon capture & storage and hydrogen transport are being developed. In part, they consist of repurposed natural gas grids. Gas flow primary standards that can provide directly traceable and accurate measurements at representative process conditions applicable to the gas grid are scarce due to their cost intensity, and historically developed only for natural gas. VSL's high-pressure natural gas flow primary standard was established more than two decades ago to provide traceability at pressures up to 64 bar(a) and flow rates up to 230 m^3/h. Recently, the usage of the standard for nearly pure CO_2-gas was assessed. This paper will present the main operational and metrological requirements set when upgrading VSL's high-pressure natural gas flow primary standard to usage with CO_2-gas and hydrogen blends with natural gas. Practical methods for fulfilling these requirements are presented and illustrated with examples. These findings will stimulate development of primary gas flow standards and realization of direct traceability for the diverse set of energy transition gases.

1. Introduction

The European Union set a target to reduce greenhouse gas emissions by 55 % by 2030 and to become carbon neutral by 2050. To support meeting these ambitious targets the Green Deal was introduced which specifically states that "priority areas include clean hydrogen, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and utilisation [1].

Carbon Capture and Storage (CCS) is a key component in national and international strategies for meeting CO_2-emission reductions according to the Climate Change Act. Hydrogen blending with natural gas in the gas grid is being implemented while development of dedicated (pure) hydrogen backbones has started, with a vision towards an infrastructure stretching across 28 European countries by 2040 [2,3]. Similar to the current situation for natural gas, reliable flow metering of CO_2 rich streams and hydrogen flows (including blending with natural gas) is needed. Showing compliance with mandatory CCS legislation, such as the EU Emissions Trading System, requires accurate flow measurement with an uncertainty below 1.5 % – 2.5 % (on total mass). For hydrogen and its blending with natural gas, typical large scale gas transmission uncertainties are within 0.15 % – 0.30 % (k = 2) range; smaller than for CO_2 rich streams because of the higher economic value of energy gases.

Recently, flow meter calibration was enabled for CO_2 at pressures as high as 150 bar and flow rates up to 1000 m^3/h [4–6]. Similarly, flow meter calibration was enabled for hydrogen blending with natural gas at pressures as high as about 30 bar and flow rates up to 1000 m^3/h [6], and for pure hydrogen at pressures as high as about 50 bar and flow rates up to about 5000 m^3/h [7]. A typical stated uncertainty level of these test and calibration facilities is at approximately 0.25 % (k = 2) or smaller. Traceability to the SI-units is obtained from the calibration of flow meters using different gases and gas mixtures and employment of reference meter models across the range (mass flow or Reynolds) in which the reference meters are used in the test facility [8].

Gas flow calibration capability including a direct link to the low-uncertainty primary level and directly at process conditions relevant for the application, is often sought to remove any doubt in uncertainty claims. For this reason, VSL upgraded its primary standard for natural gas flow for usage with hydrogen blends to natural gas. The primary standards' name is gas-oil piston prover, or simply GOPP [9]. The low uncertainty of the standard (<0.10 % on gas flow), its pressure (maximum operating pressure at 64 bar(a)), and its flow rate range (maximum flow rate at 230 m^3/h) enable to compare natural gas flow and hydrogen blend to natural gas flow calibrations. The upgraded primary standard enabled Workamp and Schakel (2021) to conclude that an indication was found that for the rotary flow meter and hydrogen blending to natural gas (<20 % H_2) considered, the meter error differences between high-pressure hydrogen blend calibration and high-pressure natural gas calibration are smaller than the meter error differences between atmospheric pressure air calibration and high-pressure natural gas calibration [10].

Since the inception of the GOPP standard for natural gas flow in 2002, it was already technically envisioned to be operationally suitable for "all types of gas" [9]. In recent years, this technical capability was exploited to address energy transition needs as part of European Metrology projects MetCCUS [1] and NewGasMet [11] by upgrading the standard for usage with CO_2 gas and hydrogen blending with natural gas, respectively. Metrology research activities are ongoing to assess meter performance [1,12] and strengthen the metrological framework in a primary intercomparison for hydrogen blend gas flow [12].

This paper will present the main safety, environmental, operational and metrological requirements set when upgrading VSL's GOPP to usage with CO_2-gas and hydrogen blends with natural gas. Practical methods for fulfilling these requirements are presented and illustrated with

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examples. These findings will stimulate development of primary standards and the realization of direct gas flow traceability for the diverse set of energy transition gases.

2. Safety, environmental, and operational requirements

2.1. Safety requirements

Specific safety requirements are applicable given the relatively large industrial scale of the GOPP. The pressure equipment directive (PED) and explosion safety requirements apply to protect against dangers from vessels and piping under high-pressure or potentially dangerous atmospheres.

2.1.1. Atmospheric safety

In its pure and gaseous form at room temperature and at atmospheric pressure, CO_2 is inert, non-flammable, colourless and odourless. As its concentration in air rises, it can cause headaches, dizziness, confusion, and loss of consciousness. CO_2 is heavier than air and can displace oxygen, particularly in confined spaces so that asphyxiation risks occur. At high concentrations it is heavier than air and will displace oxygen and may cause suffocation [13]. The GOPP is located in the Netherlands, the long-term exposure limit in the Netherlands is 5000 ppm (8 hour average), pursuant to the EU Commission Directive 2006/15/EG. While the Netherlands does not have a short term (15 minute) exposure limit, the lowest limit that can be found in Europe is 10000 ppm [14]. The risk is addressed by equipping operators of the GOPP with oxygen and CO_2 sensors to ensure the safety of the workers in case of leaks.

Hydrogen has a smaller minimum ignition energy than natural gas. Consequently, for pure hydrogen, a more stringent ATEX explosion safety gas group applies, i.e., gas group IIC (versus IIB for natural gas*)* [15,16]. For the upgrading to hydrogen blending to natural gas, first the ignition energy of the blend was determined, which, according to literature is at 0.10 mJ for which gas group IIB applies. The differences in lower and upper explosion limits were considered acceptable since they are relatively small. A similar statement holds for the limiting oxygen concentration [16]. Secondly, recommendations from a competent safety officer employed by a process safety company were followed-up. An exhaustive review was made of the electrical installation, including the explosion safety characteristics of its electrical components. Appropriate measures were taken to mitigate explosion risks to an acceptable (very low) level, such as replacing equipment suitable for use with gases from gas group IIB with gas group IIC-rated equipment. The explosion safety document was updated to include hydrogen blending with natural gas (up to 20 %) usage.

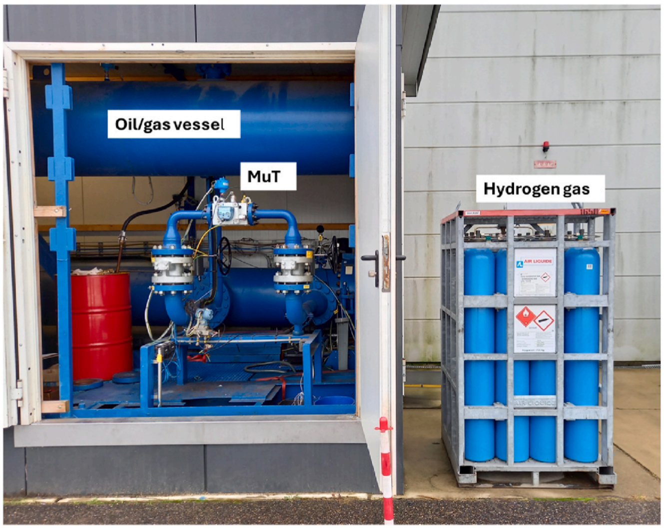

Fig. 1. Meter-under-Test (MuT) mounted on VSL's GOPP, accompanied by a hydrogen gas cylinder supply (right). A vessel filled with oil and gas is displayed in the top left part. Figure reprocessed from Ref. [10].

2.1.2. Pressure and other safety considerations

When applying for an approval for using vessels under pressure, the media types that are to be used during operations are specified. The PED distinguishes between gas groups. Piping corrosion allowances are made where applicable because the strength (steel thickness) of the pressure equipment can be reduced from gas effects on the piping. Consequently, to ensure safe use of the GOPP, a notified body was contacted to reappraise the design of the standard so that the declaration of conformity (to the PED) is valid.

The maximum allowed pressure in a cylinder can be calculated based on the following equation (ISO 13623 *Petroleum and natural gas industries – Pipeline transportation systems*):

$$P_d = \frac{2\,R_e(\theta)\,d_{min}}{D_g} \cdot \frac{1}{f} \tag{1}$$

Where:

P_d is the maximum allowed pressure,
R_e is the tensile strength of the cylinder material,
d_{min} is the thickness of the cylinder wall,
D_g is the cylinder diameter, and
$1/f$ is the design (or safety) factor.

ISO 13623 is used for transportation pipelines, and is based on CO_2 gas with impurities and different phases that accounts for steel corrosion as well. Employing (1) is the most conservative method found in literature to determine the maximum allowed pressure. For the GOPP, PED compliance was obtained, and the maximum allowed pressure from (1) is at about 70 bar(a).

Notwithstanding, well-known concerns of operation on CO_2 and hydrogen gas are potential corrosion and embrittlement of (primary standards') steel, respectively. Consequently, this was carefully assessed, see 2.3 below.

Task-risks analyses for operation of the GOPP were updated to include working with CO_2 and hydrogen blending with natural gas.

2.2. Environmental requirements

Local authorities were contacted to ensure that the applicable emission legislation was fulfilled.

2.3. Operational requirements

VSL's GOPP has an important role in the metrology framework for the high-pressure natural gas flow unit (m^3/h). One of the main drivers in its development was to achieve uncertainties below <0.10 % for natural gas reference volume [9]. It is the national standard of the Netherlands used in the harmonization group called European Reference for Gas metering (EuReGa) [17], where national metrology institutes PTB, FORCE, LNE-LADG, and VSL achieve the lowest uncertainties for the volume of high-pressure natural gas. It is clear that potential damage to the GOPP must be avoided. Therefore, a careful material compatibility study was performed for usage of the standard with pure CO_2 and hydrogen blends with natural gas. Further, a gas supply system was installed, and already existing gas sample analysis capabilities were used to determine gas mixture components.

2.3.1. GOPP's material compatibility

The GOPP components are made of various materials, which are mainly carbon steels and stainless steels. Further brass valves on the system and copper wires may be exposed to GOPP's gas. The system

Table 1
GOPP's ISO/IEC 17025 scope entry for high-pressure (natural) gas flow calibrations.

HCS code	Quantity	Range	CMC
FG 11	High-pressure gas	5 m^3/h – 230 m^3/h	0.29 % – 0.06 %

utilizes Teflon (PTFE), Polyurethane, and NBR seals. Based on a literature review, material compatibility guides and manufacturers' specifications, CO_2 is compatible with these materials in its pure gaseous form when its pressures and temperatures are lower than the critical points. NBR seals are the most susceptible to failure with CO_2 at high pressure, especially during depressurization. To avoid damage to the NBR seals, the depressurization rate must be controlled to below 10 bar/min.

In similar fashion to CO_2, a study into hydrogen embrittlement of GOPP's components was performed. It was found that while hydrogen embrittlement cannot be entirely ruled out, no literature sources indicate that embrittlement will occur for the materials used and for the operating pressures of the GOPP (maximum operating pressure at 64 bar (a)).

No-regret measures, applicable to both CO_2 gas and hydrogen blends with natural gas, are to (1) carefully purge the GOPP prior and after exposure to these gases with nitrogen gas, and (2) to limit the calibration duration itself to the time required (and not more).

2.3.2. GOPP's gas supply and gas analysis

Fig. 1 shows the gas supply system, which is composed of gas cylinders, in this case hydrogen gas, supplied separately by a gas vendor. A hydrogen blend with natural gas of desired molar fraction is created from the partial pressure ratio with respect to the operational pressure as achieved during filling with a flexible hose from the cylinder package. The GOPP has another permanent natural gas supply, which is not displayed in Fig. 1.

Representative gas samples are taken from GOPP's sampling port to accurately determine the gas components (not displayed in Fig. 1).

3. Metrological requirements

The GOPP is accredited to ISO/IEC 17025 – *General requirements for the competence of testing and calibration laboratories*. Table 1 lists the formal scope. It is applicable to "gas", resembling the fact that its metrological primary standard principle (volumetric piston prover), is applicable to various gases, and thus not limited to a particular gas (e.g., natural gas). In similar fashion, the GOPP is registered in the KCDB, the BIPM key comparison database, as a primary standard for various gases.

However, in the past two decades the GOPP was used primarily with natural gas and it is conceivable that the calibration uncertainty is affected by physical gas flow effects from CO_2 or hydrogen blending into natural gas affecting either the GOPP or the MuT. This led to the following metrological requirements for upgrading the GOPP for usage with CO_2 or hydrogen blends to natural gas:

i. Review of uncertainty budget to assess potential physical effects affecting calibration uncertainty.
ii. Ensuring GOPP's short-term metrological stability, i.e., reference values are unaltered in the short-term.
iii. Ensuring GOPP's long-term metrological stability, i.e., reference value drift is within specifications of the uncertainty budget.

3.1. Uncertainty budget review

The GOPP's best-existing devices are Instromet Rotary Piston Provers (IRPP's). Increased leakage of hydrogen along the rotors of a rotary meter, or along the piston of the GOPP may affect the calibration, particularly at low flow rates. Less dense hydrogen may affect the performance of high-pressure calibrations, of which it is industry wisdom that the denser the gas (higher pressure), the better the performance (e.g., repeatability and equivalency between standards). Fig. 2 shows viscosity (top) and density (bottom), as a function of increasing hydrogen percentage into the mixture with methane (used as first-order approximation for natural gas) at 9 bar(a) and 16 bar(a), and at 20 °C. It can be seen that the viscosity does not significantly change up to 0.20 mol/mol hydrogen in the mixture, while the density drops linearly with increasing hydrogen into the mixture. Workamp and Schakel (2021) found insignificant changes (with respect to the uncertainty) between a blend calibration and a natural gas calibration, for hydrogen blending smaller than 0.20 mol/mol. They further note that no significant changes were observed in the readings of the GOPP's leak detection system when adding hydrogen to the natural gas [10]. Their observations can be explained from negligible additional leakage as the effective viscosity from the mixture remains practically unchanged, while the density reduction is relatively small for limited blending of hydrogen into natural gas (relative to gas grid pressure variations ranging typically from 4 bar(a) to 61 bar(a)).

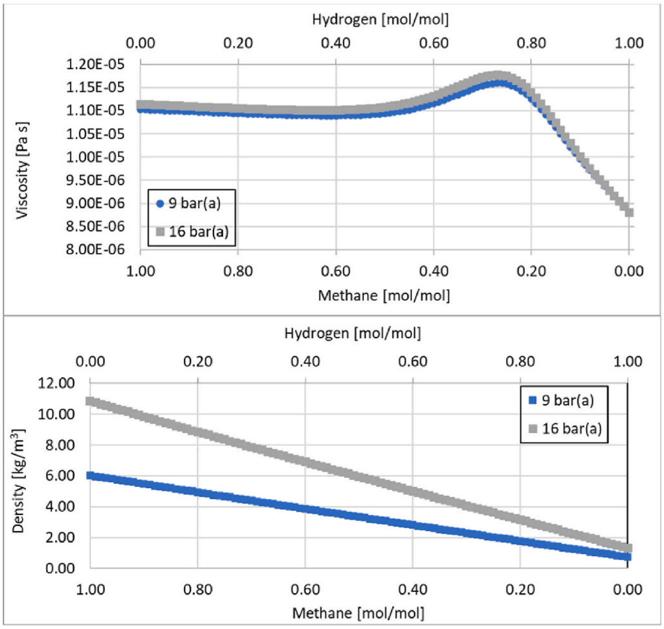

Fig. 2. Viscosity (top) and density (bottom) of methane/hydrogen mixtures as modelled using the NIST REFPROP thermodynamic modelling software [18].

3.2. Short-term stability

GOPP's short-term stability was inferred from the order of natural gas and hydrogen blend to natural gas calibrations. Fig. 3 shows the calibrations at 9 bar(a) (top) and at 16 bar(a) (bottom). The 9 bar(a) pure natural gas (NG) error curve is somewhat higher than the error curve of the 9 bar(a) hydrogen blend to natural gas error curve (HENG, 15×10^{-2} mol/mol hydrogen in natural gas, nominally). At 16 bar(a) a similar observation applies. The 16 bar(a) pure natural gas error curve was obtained first, then the 16 bar(a) HENG curve, then the 9 bar(a) HENG curve, and finally the 9 bar(a) pure natural gas curve. Since no significant difference is observed in the relation between a pure natural gas calibration and the HENG calibration, short-term stability (within the CMC) was inferred from this data.

3.3. Long-term stability

It can be conceived that corrosion from CO_2 mixtures and/or hydrogen embrittlement will affect materials of the primary standard,

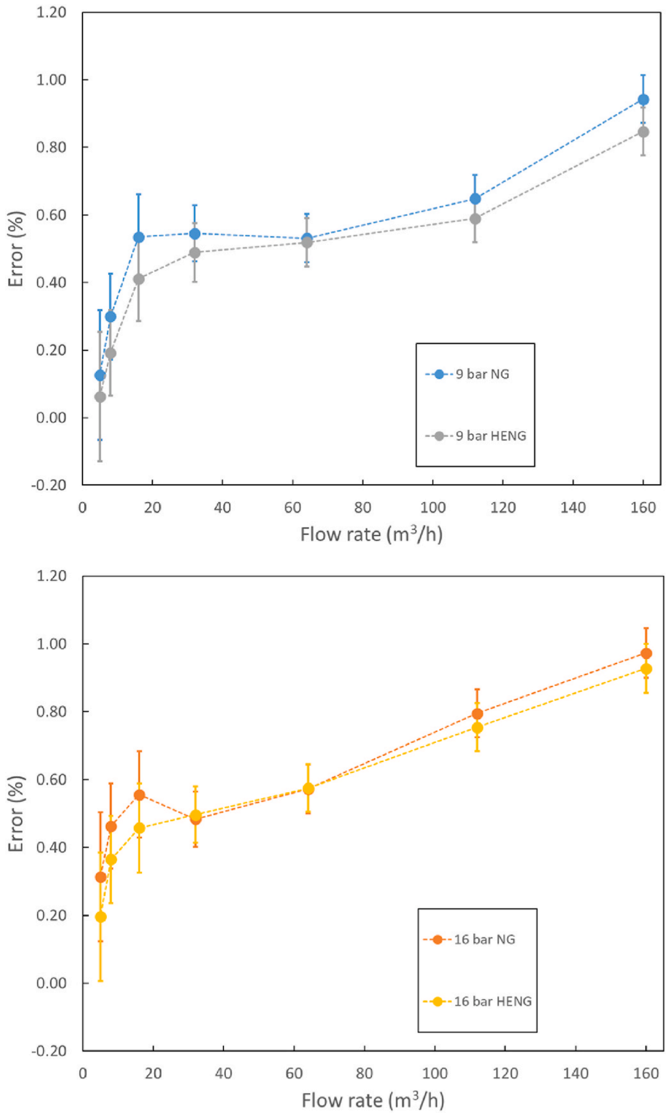

Fig. 3. Error curves of a rotary gas meter on natural gas (NG) and on a hydrogen blend with natural gas (HENG, 15 × 10^{-2} mol/mol H_2 in NG nominally). Uncertainty ($k = 2$) is indicated by the vertical bars. Figure reprocessed from Ref. [10].

that in their turn influence the uncertainty. In similar fashion, materials in best-existing devices can be affected. For this reason, durability of domestic gas meters when exposed to hydrogen was investigated within the NewGasMet project [19,20].

Long-term stability must be ensured for any (primary) standard and is a requirement for compliancy with the ISO/IEC 17025. GOPP's quality system was already in place prior to the upgrading to usage with CO_2 and hydrogen blends to natural gas. It was recently confirmed that the long-term stability of GOPP's reference volumes is within the specifications set by the uncertainty budget. No indication of effects from hydrogen blending into natural gas were observed. For CO_2 gas, no data is available yet. GOPP's long-term stability when using CO_2 gas will automatically be investigated as part of its quality system.

4. Conclusions and outlook

Current documentary standards and safety legislation enable assessing the potential of natural gas primary standards for usage with CO_2 (rich) streams and hydrogen (blending with natural gas). It was shown that VSL's existing primary standard for natural gas flow, was upgraded to usage with pure CO_2 and hydrogen blending to natural gas. The impact on enabling Europe's energy transition is meaningful because:

i. The primary standards' traceability for CO_2 and hydrogen blending is readily available, i.e., in the very near term, since the primary standard is already existing, and its CMC well-established and fully aligned with European Reference for Gas metering (EuReGa) standards [12,17].
ii. Upgrading the existing primary standard towards usage with a more versatile mix of gases of the energy transition is a cost-effective method for delivering traceability up to the primary standard level (Fig. 4).
iii. Since the primary standard is upgraded, by definition, the lowest measurement uncertainty for gas flow calibrations is achieved (Fig. 4). GOPP's CMC is below 0.10 %, well below that of test and calibration facilities accredited to the ISO/IEC 17025.

Yet, while upgrading the GOPP to hydrogen blends with natural gas was implemented, upgrading to the usage with pure hydrogen gas was not found to be possible without significant (costly) modifications. Also, the feasibility of upgrading the GOPP to the usage of CO_2 mixtures containing relatively large amounts of other components was not assessed and remains a topic for future standards' development.

While short-term metrological stability was shown when using an upgraded GOPP to usage with hydrogen blends to natural gas, data

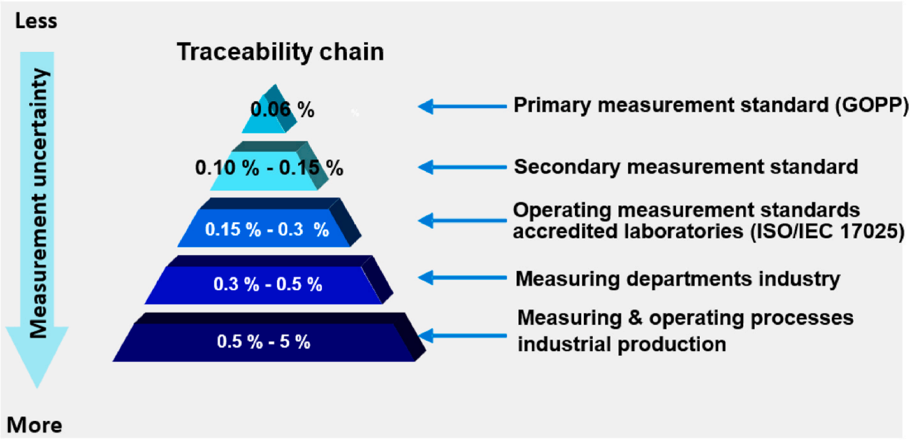

Fig. 4. Traceability chain. The GOPP is the primary standard for natural gas (and CO_2/hydrogen blend gas) flow of the Netherlands. It has the lowest uncertainty and enables calibration of secondary measurement standards with direct link the SI-units. Typical gas grid flow calibration uncertainties for the m^3/h unit are given.

proving long-term stability is continuously gathered as part of GOPP's quality system. Note that this is mandatory to meet ISO/IEC 17025 – *General requirements for the competence of testing and calibration laboratories*. Exposure to CO_2 and hydrogen blends with natural gas is limited by implementing the procedures of purging with nitrogen prior to and after calibration, and to limit the calibration duration itself to the time required (and not more; say several days in total per flow meter).

National metrology institutes will benefit from sharing experiences in upgrading and/or development of primary standards for gases of the energy transition towards a decarbonized economy. Sharing of calibration experience, data, material (in)compatibility findings, stability and durability studies will stimulate the development of a robust metrological foundation for gas flow units. This will be important to reconcile the increasing diversity in gases metered with flow meters with the need for corroborated, traceable, and low gas flow uncertainties.

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Menne D. Schakel[*], Ara Abdulrahman, Marcel Workamp
VSL B.V., Delft, the Netherlands

[*] Corresponding author.
E-mail addresses: mschakel@vsl.nl (M.D. Schakel), aabdulrahman@vsl.nl (A. Abdulrahman), mworkamp@vsl.nl (M. Workamp).