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ENABLING CCS VIA FISCAL METERING

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Abstract

Carbon Capture and Storage (CCS) will have to turn into a massive industry in order to play a significant role in the mitigation of anthropogenic climate change. The EU Emissions Trading Scheme (ETS) directive establishes that emissions captured, transported, and stored are considered as 'not emitted.' Accurate measurements will enable businesses who have implemented CO_2 capture to omit buying or selling their CO_2 Emission Unit Allowances (EUAs) under the ETS, when transferring the CO_2 to geological storages. In this context, fiscal metering technologies, calibrated and verified for CCS relevant streams, would allow rightful checks and balances in CO_2 trade. The present work provides a benchmarking study, looking into the applicability of various metering technologies for CO_2 flow measurements. The requirements to further verify the potential of such technologies in the context of industrial needs are also examined. These requirements are then incorporated into the basic design of an experimental facility with focus on operational flexibility, accurate and traceable composition and flow rate, and controlled operating conditions. The study encompasses a thorough evaluation of the metering market, including first-hand proprietary information, detailed engineering considerations for all subsystems of the experimental facility, and considerations for industrial needs based on undergoing CCS projects and plans. The study results show that although Coriolis and Ultrasonic meters seem like promising technologies for CCS, further verification at relevant conditions is required. This verification entitles a high level of innovation, particularly for accurate reference measurements for CO_2 mass and volume flow meter calibration to comply with the current regulatory framework. The results presented constitute the first step towards the construction of the world's first large-scale test facility for CCS fiscal metering technologies. The implications of such a facility are enabling fair business throughout the CCS value chain, hence levering CCS towards widespread deployment.

Keywords: CCS, Fiscal Metering, Benchmark, Measurement

1. Introduction

Carbon capture and storage (CCS) will be a vital industrial process to avoid the catastrophic consequences of global climate change caused by continued largely unchecked emissions of CO_2 and other greenhouse gases (GHG) to the atmosphere. This view is strongly supported by recent international studies [1, 2].

According to the IEA's sustainable development scenario [1][3], the estimated annual needs for CO_2 capture, transport, and storage will be at least 5 gigatonne/year by 2050. This is approximately twice the mass of natural gas transported today. With the Emissions Trading Scheme (ETS) prices above 30 € per tonne, as of January 2021, the total value of the CO_2 to be transported and stored annually according to this scenario will be more than 150 billion €. There are currently natural gas pipelines with a capacity higher than 70 MSm3/d [3], or 20 megatonne/year on the Norwegian continental shelf. Pipelines of similar capacity can be expected for CO_2, transporting the equivalent of 600 M € annually under the current ETS price. This scenario implies a high relevance of fiscal metering also for individual operators.

Within EU / EEA, the measurement instruments directive [4] establishes an accuracy for liquid CO_2 of 1.5% for the measurement systems and 1% for the flow meter itself. Flow metering technology complying with the EU regulation on the monitoring and reporting on greenhouse gas emissions (ETS M&R Regulation) [5] is needed to avoid purchasing Emission Unit Allowances (EUAs), which is vital for a viable business model for commercial CCS. Thus, finding solutions for fiscal metering is central for future industrial-scale CCS.

This framework yields the necessity for accurate metering along the CCS value chain, especially every time the ownership of CO_2 changes hands, although not limited only to custody transfer operations. In addition to being required for trading, operators will also need metering to keep track of their inventories, and governments will need accurate and certified metering to regulate the industry. Hence, accurate fiscal metering is an enabling technology for a CCS marketplace and, consequently, large-scale CCS deployment.

CCS can leverage measurement experiences fostered in the oil and gas industry, where numerous metering techniques coexist. These comprise volumetric methods such as pressure drop (e.g., orifice or Venturi), turbine, optical, ultrasonic metering, and mass flow meters such as Coriolis. However, given the notable difference in the behavior and properties of CO_2 under varying CCS conditions, against those of natural gas, the applicability of such techniques to CCS systems needs to be evaluated.

CO$_2$ poses specific challenges for flow measurement. It will be transported as pressurized liquid or dense phase, a state quite different from, e.g., pipeline conditions of water or natural gas. Further, bulk shipping is expected to take place at low temperatures, down to -50 °C, to reduce pressure. With the whole vapor-liquid equilibrium curve of CO$_2$ being close to relevant transport states, from the triple point to the critical point, properties could change rapidly with temperature and pressure.

Currently, it is not clear how traceable fiscal metering will be achieved at a relevant scale for CCS. The only technology with published studies claiming accuracies below the EU requirements is Coriolis [6], but only for pure CO$_2$ and at flow rates (3600 kg/h) far below what will be required ahead. For CO$_2$ with impurities, there are no verified results at even this scale with sufficient accuracy. Further, CO$_2$ sound attenuation is higher than for many other fluids, and the performance of ultrasonic time-of-flight (TOF) meters is yet to be independently confirmed for pure CO$_2$.

At a system level, procedures and infrastructure for traceability must be developed, taking into account relevant industrial conditions.

Against this backdrop, NCCS [7] is addressing the challenges described above through continuous dialogue with industrial stakeholders and systematic benchmarking of technologies to close knowledge gaps. The present work looks into measurement technologies with opportunities to fast-track fiscal metering for CCS deployment.

The benchmarking of the measurement principles presented in this study aims to better understand the potential of the existing commercial metering technology for CCS. The combination of proprietary know-how and research method is exploited for a thorough characterization of the most promising sensing principles and infrastructure needs for further development and verification. A discussion of the design of a test facility is presented here as a first step towards fiscal metering calibration and verification at an industrial scale.

The remainder of this paper is organized into five sections as follows. Section 2 provides an overview of the relevant regulatory framework for fiscal metering within CCS. Section 3 benchmarks promising metering technologies and discusses the planned actions to answer some of the pending questions for ultrasonic metering applicability. Section 4 establishes the need for a fiscal metering test facility and discusses the specifications and basic design for pertinent industrial utilization. The main conclusions of this study are summarized in Section 5.

2. Regulatory framework

2.1 EU regulations and directives

2.1.1 EU Emission Trading System (ETS) regulations

The current basis for fiscal metering regarding the European ETS is provided by the ETS M&R Regulation 2018/2066 [5]. From the text in Article 49, regulations for the transfer of CO$_2$, and Annex VIII, Section 1, Tier 4, it can be deduced that the required accuracy for measuring the net captured CO$_2$ mass is 2.5 % on an annual basis. This is a relaxation from the previous and often quoted limit of 1.5 % specified by the now superseded Commission Decision 2010/345.

Article 42 of the M&R Regulation specifies the legal requirements to establish these estimates, which is to follow standards where available. Where no applicable published standards exist, suitable draft standards, industry best practice guidelines, or other scientifically proven methodologies shall be used. Hence, developing such best practice/scientifically proven methodologies is a significant motivation for the fiscal metering activity of NCCS.

2.1.2 EU measurement instrument directive (MID)

The EU MID (Directive 2014/32) [4] was written to harmonize the laws of the EU and EEA member countries on measurement devices. It has been in force since 2016. Of particular relevance for CCS, Annex VII provides regulations for continuous measurements of liquids other than water. Different accuracy classes are defined, and for liquid CO$_2$, the accuracy class 1.5 is specified. This means that the whole measurement system should have an accuracy of 1.5 %, but the meter must have an accuracy of 1.0 %. Further, a minimum 4:1 turndown ratio is specified. It also sets specific accuracy limits for associated measurements needed to convert the measurements into a mass flow. The accuracy limits are 0.5 °C in temperature and 2 kg/m^3 in density. For pressure, the limits are 50 kPa below 10 bar, 5 % between 10 and 40 bar, and 200 kPa above 40 bar.

2.2 Other standards and recommendations relevant for CO$_2$ fiscal metering

2.2.1 OIML R 117

OIML is the international organization for legal metrology. The principal recommendation of interest to CCS is OIML R 117 ‘Dynamic measuring systems for liquids other than water.’

The metrological and technical requirements applicable to dynamic measuring systems for liquids other than water are specified in the OIML R 117-1 [8]. Based on the field of application, the measuring systems are classified into four accuracy classes. The measuring systems for liquefied CO$_2$ belong to Accuracy Class 1.5, which requires an overall accuracy of the complete measuring systems of 1.5 %. This is in agreement with EU MID. Also, R117-1 specifies that the maximum permissible errors for a meter under rated operating conditions is 1 % for the measuring system of Accuracy Class 1.5.

2.2.2 NIST Handbook 44 – 2017

NIST is the US National Institute for Standards and Technology. NIST Handbook 44 – 2017 [9]. Section 3.38 covers the code requirements applicable to liquid-measuring devices used to measure liquid CO$_2$, though not all of it applies to large-scale flow. The measurement of liquid CO_2 is classified as Accuracy Class 2.5 with an acceptable tolerance for the measuring devices of 1.5 %, and the test liquid shall be CO_2 in a compressed liquid state.

2.2.3 ISO standards

There are several ISO standards relating directly to different metering technologies. Some of these standards only cover high-level guidance, e.g., ISO 10790:2015 [10] for Coriolis meters. Others, such as ISO 5167-2:2003 [11] for orifice plates, are very detailed. There are also standards ISO 12242:2012 [12] and ISO 17089-2:2012 [13] for ultrasonic meters for liquids and gas, respectively. ISO/IEC 17025:2017 [14] establishes the general requirements for the competence of testing and calibration laboratories.

2.3 Comparison between NCCS specifications on accuracy and existing regulations, standards, and recommendations

As seen above, the M&R regulation, which specifies a mass accuracy of 2.5 %, appears not to be entirely in agreement with the MID and OIML R 117, which defines a measurement system mass flow accuracy of 1.5 %. One interpretation could that the MID regulates the accuracy needed for a measurement system at a given point, and the additional 1 % allowed under the M&R Regulation accounts for other uncertainties in the CCS chain regarding the stored CO_2 mass. It should also be noted that the ETS regulations are still under regular review. In either case, 1.5 % mass flow accuracy seems like a sensible criterion when evaluating mass flow metering systems after considering the available regulations and recommendations. Note that both MID and OIML R 117 establish a 1.0 % accuracy for the flow meter itself.

Verification of a fiscal meter requires a reference flow with accuracy much higher than the meters' specification.

3. Benchmarking of flow metering methods for CCS

3.1 Flow metering technologies with potential for CCS

There exists a great variety of flow metering technologies, including Coriolis flowmeters, orifice plates, ultrasonic meters, turbine meters, venturi meters, vortex meters, tomography, radiation attenuation densitometry, SONAR-based meters, and nucleonic-based meter. Three technologies that have been identified as particularly relevant for CCS applications will be discussed in the following.

3.1.1 Coriolis flowmeters

Coriolis flowmeters use the Coriolis effect to directly measure the amount of mass moving through the meter. Thus, it has the advantage over volumetric flowmeters that pressure and temperature measurements by separate equipment are not required to convert volumetric flow rate into mass flow rate. Coriolis flowmeters have been tested for pure CO_2 in gas, liquid, two-phase, and supercritical phases covering a limited condition, such as a temperature range of 17 – 30 °C and pressure range of 54 – 85 bar [6, 15, 16]. The uncertainty is higher with impurities [17-19] but probably still acceptable for ETS. However, no verification has so far been performed at flow rates relevant for full-scale CCS, lower temperatures, or other normal operational conditions. The influence of temperature variations of fluid or the ambient environment has not been systematically studied yet.

3.1.2 Ultrasonic flowmeters

The ultrasonic flowmeters (USMs) measure the velocity of a fluid with ultrasound to calculate volume flow, using time of flight or frequency. Over recent years, ultrasonic technologies have been developed to overcome the measurement challenges of CO_2, which includes the use of more sophisticated and powerful signal processing features and diagnostics. USMs have been evaluated in the application of CO_2-rich natural gas [20, 21], and flow meter suppliers have expressed that the issue of acoustic attenuation can be handled. Nevertheless, this remains a main uncertainty regarding the applicability of USMs for CCS in different relevant functions. Apart from signal attenuation, the measurement uncertainty of USMs is dependent on the accuracy of density measurement, flow conditions, temperature and pressure process conditions, etc. The ultrasonic flowmeters have the potential to provide high accuracy, non-invasive CCS measurement system, and zero to no pressure drop, provided their performance is fully characterized for the given high sound attenuation of CO_2.

3.1.3 Orifice plates

The orifice metering technology measures the pressure drop before and after an orifice plate, and the flow rate can be obtained from Bernoulli's equation using coefficients established from extensive research. The orifice plates have been used in the facility in the In Salah CCS demonstration project and a pilot capture plant operated by Vattenfall AB. There are, however, no demands on accuracy since no regulatory reporting requirements were involved in these schemes. Orifice plates are attractive due to their inherent simplicity. In addition to an unavoidable pressure drop, the main weakness of orifice plate meters is probably their inflexibility regarding the fluid flow rate and properties. Compared with many other fluids, CO_2 properties have a rather high sensitivity to temperature, pressure, and small amounts of impurities at relevant conditions.

3.2 Benchmarking

Table 1 summarizes the potential of the metering technologies assessed for CO_2 transport.

Table 1: Summary of benchmarking study for the potential metering technologies

	Coriolis	**Ultrasonic**	**Orifice plate**
Fiscal accuracy class (OIML R117)	0.3	0.3	-
Measurement range (10”)	~1,000 tonnes/hr (nominal)	1824 m^3/hr	Similar to Coriolis, but small turndown permissible without affecting accuracy
Process pressure limit	SS316, 100 barg, SS318 / Hastelloy C22 200 barg	No fundamental limit for clamp-on for liquids or inline (>176 bar installed).	Not a limitation in practice
Process Temperature range	Sufficient (e.g., KROHNE commercial models can be specified from -200 to +400 °C)	Sufficient (-190 to +500 °C depending on options and models)	Pressure transducer dependent, but little flexibility once calibrated for a fluid
Ambient temperature (°C)	-40 to +65 °C	-40 to +65 °C	Pressure transducer dependent
Composition ranges	In principle, unlimited and flexible as long as single-phase is ensured, but must be verified	Higher impurity level can give higher signal strength, but more uncertain density (if based on EOS)	In principle, unlimited and flexible as long as single-phase is ensured, but more uncertain density (if based on EOS)
Pressure drop	Yes	Can be negligible	Yes, and it could be strongly tied to accuracy
Multi-phase	To a limited degree and with lower accuracy	Normally not	No
Density relation	The meter can inherently also be used as a densimeter, but density does not have a first-order effect on the mass flow measurement	First-order impact, external measurement, or model estimate required	First-order impact, external measurement, or model estimate required
Weight and footprint (10”)	~900 kg, 0.85 m^2	0.09 m^2 / 4 beams ~530 kg	Relatively small
Recalibration interval /method	Interval not specified. Method depends on required uncertainty	Interval not specified. Method depends on required uncertainty	Interval not specified. Method depends on required uncertainty
Long-term measurement stability	Not defined	Not defined	Not defined
Installed costs	High	High	Low
Flange dimension	10” may be a practical limit for the purpose	TBC, most likely no limitations	Any
TRL (Scale of EC and for CO_2 transport)	4	4	9
Knowledge gaps	Verification at varying conditions	Properties, especially attenuation, transients	Properties
Zero stability (10” pipe)	< 50.0 kg/hr	< 0.18 m^3/h	High uncertainty with high turndown
Flow conditioning	Not required	For a 4 path meter, either: • 20D upstream - flow meter - 5D downstream, or • 5D upstream - flow conditioner - 10D upstream - flow meter - 5D downstream D is the nominal diameter	Flow conditioner required

3.3 Further evaluation

In NCCS, actions are being undertaken to perform static tests of an ultrasonic flow meter as a first step to evaluate the use of such technology for fiscal metering of large-scale CCS systems and partially close pending knowledge gaps identified above. The planned tests will monitor signal strength, speed of sound, and receiver diagnostics at relevant temperature and pressure ranges for CO_2 transport. The tests will also verify zero flow measurement when using the flow meters for liquid CO_2.

An ultrasonic multipath, transit-time-based meter will be tested at SINTEF Energy Research laboratories in Trondheim. The experiments consist of filling the meter’s body with liquid CO_2 and measuring the signal output at various conditions relevant for CO_2 transport, as illustrated in Figure 1. The response of the sensors will be characterized as a function of fluid temperature and pressure. The temperature will be controlled within ±1 °C by enclosing the vessel in a temperature-controlled chamber.

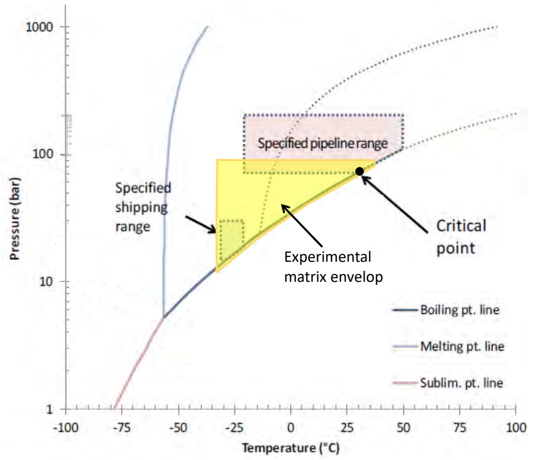

Figure 1: Experimental envelop for ultrasonic CO_2 static tests

4. Flow loop for fiscal metering testing

The benchmarking above discussed the potential of orifice plates, Coriolis, and ultrasonic meters for CCS. Each technology has an operational envelope that makes them suitable for particular applications. The complexity of the CCS process, as different industrial CO_2-rich sources are incorporated into the value chain, precludes the development of a generic fiscal metering solution enveloping all possible conditions. This, however, creates a potential for distinct application niches for the various metering solutions, hence providing opportunities for utilization for a variety of technologies.

A recent ZEP report [22], targeting opportunities and challenges of Trans-European CO_2 transportation infrastructure for CCUS, highlights that testing different measurement technologies, under representative conditions and compositions, is a necessary step towards determining suitable metering solutions. To do so, a large-scale test facility for CCUS pipeline and metering technologies needs to be constructed, as no full-scale test facilities for calibration of flow meters under real liquid or two-phase CO_2 process conditions exist today [23].

Within NCCS and a national project for CCS research infrastructure for ECCSEL ERIC [24] (ECCSEL NFS), the design of such a facility has been thoroughly addressed. The following subsections provides the specifications defined for the planned experimental facility. The design aims to be industry-relevant and target high TRLs in measurement technologies. A high-level description of the basic design is also provided.

4.1 Facility specifications

The design parameters for the research facility and subsystems were defined following two workshops and several discussions with NCCS industrial partners, including end-users and operators. The premises for the facility's specification on capacity and accuracy comprise:

- The accuracy in mass and volumetric flow measurement should be significantly higher than the ETS requirements [5], the EU MID [4], and the NIST [9] recommendations.

- Fluid under tests must be in single (liquid) phase.

- The flow rate should be in the range of 200-600 tonnes per hour to make the facility relevant for flow metering in full-scale projects.

- The facility's pressure range should be as close to real transport conditions as possible to mimic real transport scenarios.

- The facility should be able to satisfy stability and accuracy requirements in line with the General requirements for the competence of testing and calibration laboratories standard ISO/IEC 17025.

-The facility's loop size should be as close as possible to the actual measuring instrument sizes (8-12" range).

The specifications provided in Table 2 encompass capacity, temperature, pressure and composition ranges, and accuracy of the measuring variables, i.e., mass flow, volume flow, and density.

Table 2: Specifications for CO_2 fiscal meter test facility

Parameter	Specification
Mass flow accuracy	0.25 %
Volumetric flow accuracy	0.25 %
Accuracy in density	1.2 kg/m3
Max flow rate (t/h)	600
Min flow rate (t/h)	50
Max flow (m3/h)	800
Phase state	Liquid / dense phase
Pressure (bara)[a]	Up to 120
Process temperature (°C)	4 to 40
Ambient temperature (°C)	-20 to 25
Composition range (mole fractions)	
CO_2	≥75 mol%
N_2	≤ 25 mol%
Ar	≤ 25 mol%
H_2 (TBC)	≤ 10 mol%
CH_4 (TBC)	≤ 23 mol%
H_2O	≤ 350 ppm
O_2	≤ 10 ppm
H_2S	0
CO[b]	-
SOx[b]	-
NOx[b]	-
Amines	0
Reference fluids	Pure water
Meter pressure drop (bar)	< 2
Test section length	20 m
Development length (upstream / downstream meter)	15 m /4 m
Pipe dimension (inches)	10
Reference normative	ISO 17025, OIML R 117

[a] Minimum pressure is the evaporating pressure at a given temperature plus a safety margin to avoid vapor phase formation.
[b] May occur as impurity in other source gases.

4.2 Basic operation and design

The facility has been designed to enable testing and calibration of sensing technologies and flow meters for CO_2-relevant mixtures; the focus is on traceability, flexibility, and accuracy.

An overview of the facility is sketched in the diagram shown in Figure 2. The system encompasses a highly instrumented recirculating loop filled and pressurized from an external source into a buffer tank. The circulation of the CO_2 mixture is provided by a liquid pump. A cooling unit downstream the pumping system ensures thermal control of the process.

A flow straightener upstream of the metering technologies under test (MUT) ensures a fully developed flow profile without distortions at the inlet of the flow meters. Flexibility in the design allows for the testing section to be easily substituted with one of different dimensions to accommodate various flow meter sizes.

Accurate densimeters are placed upstream and downstream of the MUT. These measurements will be compared with integrated density measurements which some flow meter types and models have.

Mixture composition is measured using a gas chromatograph (GC). The fluid must be in single-phase, i.e., liquid or dense phase, throughout the circuit during the test runs; otherwise, the composition of the mixture will vary, and GC sampling would yield unrepresentative results.

Accurate measurement of volume or mass flow is ensured through a two-step process. A primary reference is used to calibrate an array of flow meters. These calibrated meters will henceforth be applied as secondary references for tests/calibration of the MUT. The array of meters is designed to be chain calibrated against the primary reference unit. The capacity of the primary reference must match that of the second reference flow meters. The number of flow meters in the array is determined by the capacity of these meters, and hence of the primary reference, and the targeted maximum flow (600 t/h). The aim is to have a reconfigurable system to accommodate for a primary-secondary reference calibration of all the meters. The strategy of using multiple parallel secondary references is employed by other labs, e.g., for LNG [25, 26] or natural gas [27]. These must, however, be calibrated against a traceable reference at steady state under the temperature and pressure conditions specified in the test matrix.

Depending on the type of MUT, it could be of interest to reference both for volume and mass flow rate. Reference measurements of liquid mass flow are usually based on gravimetry and timing, while a reference for volume flow rate could be based on volume and time measurements. For mass, volume, and time, there are measurement practices resulting in accepted estimates of uncertainty [8, 28-30].

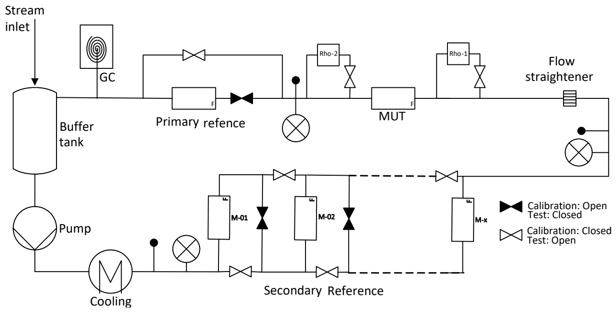

Figure 2: Schematic of an experimental facility for CO_2 metering

4.2.1 *Primary reference technologies*

The primary reference is the single most crucial system in the loop for accuracy and traceability. Following, two possible solutions for primary references of CO_2 streams are discussed.

One possible method consists of diverting the flow to a closed container. This, however, involves accurate back pressure control at the tank inlet to maintain the pressure. Such a valve and control system, suitable for the high flow rates and pressure drops that will occur, requires advanced custom-made components. The possibility of dry ice formation must also be taken into consideration. During the rig operation, close control of the pressure, above boiling point, must be ensured in the buffer tank. Avoiding fast boil-off and subsequent temperature drop, in hand with control of the fast dynamics of the system's temperature, guarantees uniform composition of the circulated stream.

Another solution is that of readily available direct volumetric primary reference combined with derived mass calculation. Volumetric meter proving is a method that has been long implemented in the industry, ever since advancement in the pulse interpolation techniques allowed for the development of provers of smaller scale, i.e., small volume provers (SVP)[31]. Volume proving consists of a traveling piston, which is used to measure volume flow. The position of the piston within the proving cylinder, which corresponds to a calibrated volume, is detected by optical switches located at different positions along the piston trip. The addition of a densitometer and accurate pressure and temperature measurement would allow direct and indirect, respectively, estimates of mass flow from the measured volume flow. API standard section 4 [32] establishes that Provers must have an uncertainty of less than ±0,01 % for all measurements relating to meter proving, including uncertainties in temperature, flow, and pressure. SVPs are made for applicable flow rates and pressures, and both Emerson and Honeywell claim repeatability of the order of 0,02 % [33, 34] for water flow. However, no accuracy numbers are provided, and it is an open question how accurate and repeatable the provers are with more compressible liquids like CO_2.

4.2.2 *Secondary reference: preliminary uncertainty assessment*

A preliminary uncertainty analysis was performed for the secondary reference array proposed in the facility schematic. Assuming the meters of each reference stage i has a relative repeatability of $u(i)$, the uncertainty contribution for each meter is $\sqrt{2}u(i)$. The total relative uncertainty contribution of the calibration stage is then in the interval $\sqrt{2}u(i)\left[\frac{1}{\sqrt{N_{p,i}}} \quad 1\right]$, where $N_{p,i}$ is the number of parallel arms of stage i. The maximum is reached if the fluctuations of the meters in the arms of the stage have a correlation of 1. The minimum value is assumed if the fluctuations of the stage meters are independent of each other. The real case is probably somewhere in between. Assuming that the relative repeatability of the meters of each stage is the same $u = u(1) = u(2) \ldots$, and the number of parallel meters in each stage is the same $N_p = N_{p,1} = N_{p,2} = \cdots$ we get the limiting cases provided in Table 3, where N_s is the number of stages. Hence, $N_s = 1$ in the base case scenario of Figure 2.

Table 3: Preliminary uncertainties of secondary reference

	Independent arms & stages $\sqrt{\frac{2N_s}{N_p}}u$	Independent arms, correlated stages $N_s\sqrt{\frac{2}{N_p}}u$	Correlated arms, independent stages $\sqrt{2N_s}u$	Correlated arms & stages $N_s\sqrt{2}u$
$N_s = 1$ $N_p = 9$	$\sqrt{\frac{2}{9}}u = 0{,}47u$	$\sqrt{\frac{2}{9}}u = 0{,}47u$	$\sqrt{2}u = 1{,}41u$	$\sqrt{2}u = 1{,}41u$

5. Conclusions and further work

There are several potential issues associated with the accurate measurements of CO_2 mass flow in CCS systems due to the behaviour and properties of CO_2 and the expected CCS conditions. Three flow metering technologies were found most promising; after being reviewed, their benefits and limitations with respect to the measurement of CO_2 in CCS schemes were addressed. Coriolis seems like a promising technology for CCS due to its high accuracy and no apparent showstoppers for CCS except perhaps scalability and pressure drop, but this remains to be verified. Similarly, for ultrasonic meters, which have become popular for natural gas, the impact of the high acoustic absorption of CO_2 flow requires dedicated assessment. In this sense, in NCCS, efforts are being undertaken to evaluate the attenuation of sound at relevant pressure and temperature conditions of liquid CO_2 transport.

The benchmarking study also showed that there is no current single metering system that can fulfil all of the requirements for the various CO_2 metering needs, in particular when impurities are present, or the physical conditions are varying. Further, at present, no technology has been verified at the accuracy required by ETS at industrially relevant flow rates for pure CO_2. Existing measurement technologies should hence be further developed and validated for different CCS applications and be experimentally evaluated and verified to the accuracy required by ETS.

There are no test facilities or established methodology for testing CO_2 flow meters at an industrial scale under transport conditions. Methodologies and procedures used for gases or incompressible liquids must be modified for accurate verification of CO_2 flow metering technology. The specifications of an industrial-sized facility for verification of CO2 fiscal metering were provided, along with a high-level discussion on the basic design of such facility and subsystems. Primary reference measurements of CO_2 mass and volume flow will require innovative solutions and specialized components (pumps, valves, temperature control, etc.).

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