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Technical Paper

The Certainty of Uncertainty in Uncertainty in Subsea CO2 Metering

Alistair Collins, Solartron ISA (AMETEK)
Chris Waller, Solartron ISA (AMETEK)
Alan Downing, Solartron ISA (AMETEK)

1 INTRODUCTION

With the increasing push for decarbonisation, the accurate metering of CO2 injection into subsea wells is increasingly relevant, and the development of suitable measurement systems is an urgent worldwide priority. However, with the legislation for allowable measurement uncertainty across different markets in the process of formalisation, this has led to increased uncertainty in what is required. Similarly, with flow loop facilities using CO2 starting to come online, and updated public domain PVT models still in development, testing of suitable meters on these fluids has recently begun.

This paper will examine these aspects through the lens of the development of Solartron ISA's Carbonstream flow meter, including Technology Readiness Levels. Based on thirty years of experience of subsea metering (including gas, water and methanol injection, gas lift, and wet gas), Solartron ISA have designed a fit-for-market CCUS metering product, developing a suitable flow meter when the only certainty appears to be the uncertainty in the uncertainty of the measurement.

2 SETTING THE SCENE

The Paris Agreement [1] was a key outcome from the UN Climate Change Conference (COP21) in 2015 (coming into force in November 2016). This treaty, ratified by 196 signatories, states the clear goals of holding "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." The UNFCC states that "to limit global warming to 1.5°C, greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030" [1].

Carbon Capture and Storage (CCS) is a pivotal technology that can help to address this urgent challenge due to its ability to significantly reduce the carbon dioxide (CO2) emissions at their source, and to begin to address the CO2 already in the atmosphere via carbon dioxide removal (CDR) technologies.

The UN's Intergovernmental Panel on Climate Change (IPCC) report on "Global Warming of 1.5°C" [3] indicates that somewhere between 350 and 1200 gigatonnes (Gt) of CO2 will need to be captured and stored this century. Similarly, the International Energy Agency's (IEA) Net-Zero Roadmap states that around 7.6 Gtpa (gigatonnes per annum) of CO2 will need to be captured by 2050 [4]. The CCS projects currently in operation have the ability to capture and store around 50 megatonnes per year (i.e. 0.05 Gtpa) of CO2; therefore, an increase of around 150-fold on currently capabilities is required to meet these existing targets.

Using the UK as an example, the UK Climate Change Committee stated in 2019 that CCS Technologies are a necessity, not an option for the UK to meet its NET ZERO targets [5]. This will require important contributions from CCS in industry, for hydrogen production, combined with bioenergy (e.g. for power generation) and in flexible fossil-fired power generation, which together is estimated to require between 0.075 and 0.175 Gtpa by 2050 for the UK alone. However, the UK has an estimated 78 Gt of offshore storage potential, with current project expected to provide 0.05 Gtpa storage by 2035.

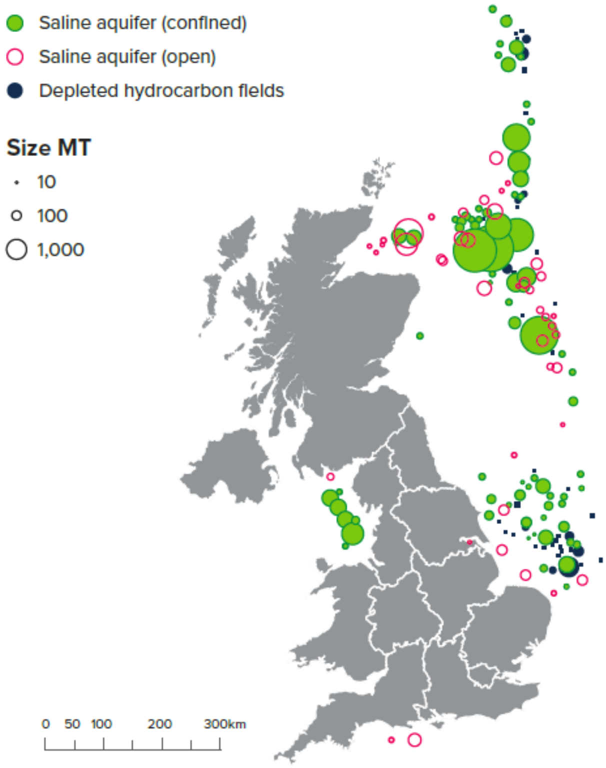


Figure 1 - Map showing storage potential in the UK North Sea [25]

Whilst storing the captured carbon dioxide is critical, there is also the need to account for the CO2 being transported and stored, which therefore requires flow metering. The European Emissions Trading Scheme (ETS) provides a "cap and trade" framework where the cap is a limit that is imposed by the EU and decreases over time to meet their climate targets. The trade aspect allows emission allowances to be traded as part of auction. This system requires that companies must monitor and report their emissions on a yearly basis, and "pay" for them with emission allowances (or face a heavy fine). This sets up a market in the "price" of CO2, and thus "provides an incentive for companies to reduce emissions cost-effectively." [6]

The UK has been drafting the CCS Network Codes [7] to codify an Emissions Trading Scheme, where such companies are paid for the mass of rich CO2 transported and sequestered. As per the EU ETS, this document – and many similar ones across the world – will need to state the uncertainty in the flow measurements that are allowable to remain compliant. As the tongue-in-cheek title of this paper indicates, this is still a work in progress across the world, leading to some uncertainty in the uncertainty of these CO2 measurements.

What is clearly a necessity is the metering of carbon dioxide dominant flows at increasingly large industrial flow rates, and appropriate to the specific physical challenges that CO2 metering presents. It would therefore appear beneficial for flow metering equipment to be purpose built for these opportunities.

This paper includes aspects of the development process that has occurred for one particular CO2 flow meter as an example of the changing understanding of what is required over the last few years. Recent development and flow testing will be considered, as well as early meters already going into service. A more detailed consideration of CO2 flow measurement and the associated uncertainties will lead into a brief contemplation of what the future of this field may look like. It is hoped that this will stimulate further discussion in many areas associated with CCS and CO2 metering, leading to improvements across the industry.

3 DEVELOPING A FLOW METER

Although the purpose of a flow meter is known – to accurately measure the fluids that pass through it – the development of a new meter relies upon determining what key aspects are required, and what compromises are acceptable to the customer and end user. Where the field of measurement is uncertain, as is the case with CCS metering, the development process must consider the alternatives that may be taken over the subsequent years, such that the developed product may remain relevant, even if some initial assumptions alter over the full product lifecycle.

The application of the “Kaizen” philosophy – which is Japanese for “change for the better”, or continuous improvement – provides a useful starting point, with one form of this methodology involves five steps:

- Knowing your customer (identifying the problem)
- Let it flow (analyse the problem)
- Go to Gemba (develop solutions)
- Empower people (implement solutions)
- Be transparent (review and standardise)

For the example of the Solartron ISA Carbonstream meter, detailed pre-work and analysis resulted in a stronger and more coherent flow meter design that met a wider set of objectives for a successful new product. Detailed development of the flow meter design, including CAD models, bench-top prototypes of the sensor and electronics package, and software for the PVT and flow metering algorithms, provided means for verifying the project at an early stage. Engaging directly with key external stakeholders, and with a wider audience through webinars and conferences allowed for a greater variety of pertinent questions than might otherwise have been the case.

In any product development, the voice of the customer (VOC) is an essential input. In established markets, such as oil and gas exploration, requirements are relatively well understood, even when developing products with new technologies and techniques. However, in emerging markets where requirements are still being developed, codes and standards are not available, and the entire value chain process – from capture, through transmission, and eventually to storage – is being developed, VOC is essential, but significantly more challenging to obtain.

Was it easy to get VOC from the industry? Yes! This may be surprising, but one word that immediately springs to mind when reviewing this process is “collaboration”. This term reflects the general lack of knowledge a number of years ago. Few people had firm facts and figures, but there was a strong willingness to share existing knowledge and learn more in return. In other words, even the customers were in discovery mode.

From this VOC it was clear there was a wide range in measurement expectations, ranging from ±1% to ±5%. One notable point was that the subsea meter was the final measurement in the system, which is the opposite of how oil and gas meters are typically used in current wellhead applications. Other aspects that remain topics of conversation include the lack of calibration facilities and the absence of suitable equations of state (EOS) – where both remain critical topics, although there has been progress over the last couple of years.

Additionally, the VOC highlighted different economic considerations and the potential simplification of subsea equipment. These insights eventually led to the Carbonstream meter including an upgraded flow calculator and enhancements in temperature measurement.

3.1 Development Processes and Technology Readiness Levels (TRL)

The development of new technologies benefits from a systematic methodological approach, with clearly documented expectations of outcomes and stages that can be implemented across the development team. There are many different approaches, but the use of stage "gates" provides a decision-making opportunity for multiple project stakeholders to influence the development at key points in the development project.

Whilst many different development methodologies can be utilized, a more standardised approach to the qualification of new equipment, particularly for subsea equipment, is provided by API 17Q Recommended Practice on Subsea Equipment Qualification [9]. This "…is intended to provide high-level guidance only, so that the industry will have a common set of principles to follow for equipment qualification." It is also worth noting that although developed for subsea equipment, this process can be equally applied to non-subsea equipment. Whilst the detail of this process is beyond the scope of this paper, a key aspect of the API 17Q practice is the definition of Technology Readiness Levels (TRL) as stages for identifying the current qualification progress of a product development:

- TRL 0 – Basic Research
- TRL 1 – Concept Development
- TRL 2 – Concept Demonstration
- TRL 3 – Prototype Development
- TRL 4 – Product Validation
- TRL 5 – System Integration Testing
- TRL 6 – System Installation/Commissioning
- TRL 7 – System Operation

TRL 4 to 6 may be classified as "proven technology", whilst only TRL 7 is accepted as "field proven", and that may require the product to have been operational in the field for multiple years.

In the context of product introductions in the oil and gas industry, it is often said that it is a "race to be second". Users prefer to let others take the initial risks and only adopt a technology once it has been tried and tested, typically at TRL 7. However, in an emerging market, this approach is not feasible. Opportunities to gain experience are limited, and we have observed that most users are being pragmatic and have adjusted their expectations to TRL 5.

3.2 Technology Incorporation and Integration

Few development projects start with a completely blank slate. A flow meter of any sort is made up of a number of components, such as input sensors, electronics for signal processing, computation and flow calculations, and for outputting the data over a communications connection. Subsea flow meters are no different, although making specific allowances for the harsh environment the meter will be subject to, such as the external and internal pressures, temperatures, etc.

Solartron ISA's range of single phase "Seastream" meters utilize a SST3010 DP subsea differential pressure transmitter (a marinized version of a Yokogawa EJX130A DP instrument) incorporating an in-house developed communications board suitable for subsea communications protocols (such as Modbus or CANbus). A recent update to this electronics board was necessitated due to the main processor coming towards end-of-life, and the updated chip provided significant improvements to the processing capabilities. Upon investigating this new-found potential, it was determined that it could be utilized to provide a full DP flow calculation, under the "FloCalculator" brand name, using the pressure from the transmitter secondary variable, and an input for the fluid temperature. As this didn't exhaust the additional computational capabilities, the Carbonstream meter design could additionally include two further features within this new meter design.

This evolution of the FloCalculator firstly incorporated a Non-Intrusive Sensor (NIS) for the determination of temperature. A temperature probe measures the body temperature of the Venturi close to the flow without penetrating into the flow itself, and thus creates no additional leak path. The process temperature can be calculated from this measurement, an ambient temperature measurement, and a coefficient. In this manner, an accurate-enough measurement of the fluid temperature can be made without necessitating a thermowell and the additional hardware and calculations this requires. Solartron ISA have been using this technology in topside applications for some time – particularly for the Dualstream range of wet gas meters – and so extending its applicability to subsea metering was determined to be of low additional risk to the development project.

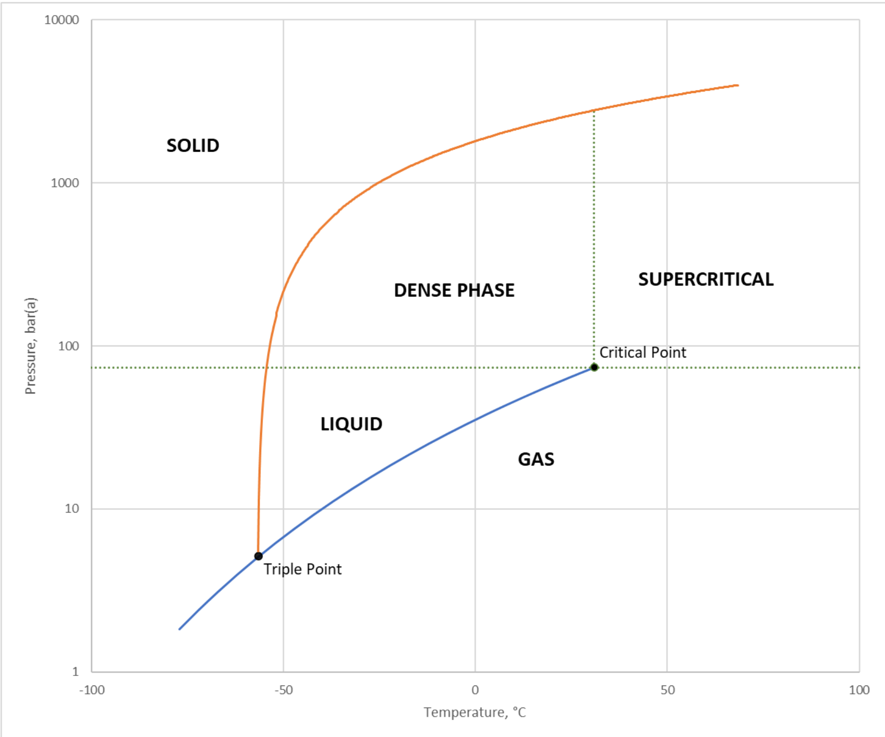


Figure 2 - PVT Diagram for pure CO2

Secondly was the addition of an Equation of State (EoS) for calculating the fluid properties of the CO2-based fluids expected for the Carbonstream flow meter. The FloCalculator product range already includes polynomials in pressure and temperature for these required parameters for calculating the flow rate, and these can be fitted to any given EoS or physical data to provide flexibility to the end user. However, these are best correlated over a range of line pressure and temperatures, and the uncertainty associated with their use may increase outside of this characterised region. A full single-phase Equation of State, such as GERG-2008 [10] (or more formally, the ISO 20765-2 [11] implementation of GERG-2008, as this allows for the computation of the required parameters) offers more flexibility on the pressure and temperature range, and is fitted across the phase transition that may be seen with CO2 fluids. Note, however, that although this can be for gas, liquid and dense phases of CO2, these calculations are for a single phase, and therefore currently there is not a suitable multiphase solution.

The importance of this was to create an integrated single solution to provide a flow rate output for CCS flows, such that it is mostly a plug-and-play instrument.

Figure 3 – Render of a Carbonstream Flow Meter

3.3 Meter Design

Mechanically, the Carbonstream is based on BS EN ISO 5167-4 [12] standard Venturi meter, with fully redundant sensors. The design is therefore suitable for the harsh subsea environment and corrosive conditions that may be associated with CO2 flow, including operation down to 3000 m water depth and process design pressure to 690 bar(g). Solartron ISA's previous experience has demonstrated that this type of meter is extremely resilient, with no recalibration required during its life, and is additionally suitable for multiphase applications, if or when they were to occur.

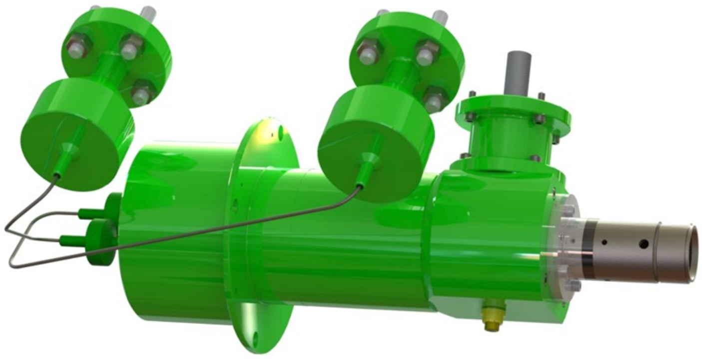


Figure 4 - SST 3010 MV, with diaphragm seals and integrated temperature sensor

The SST3010 DP sensor is connected to the meter using compact diaphragm seals which are arranged such that there is minimal distance between the differential pressure tapping and the remote seal diaphragm. The diameter of the diaphragm seal is such that the additional measurement uncertainty is kept to a minimum. For a CCS meter, this means that if the operational conditions were to change from gas to liquid/dense phase fluids that the DP measurement should still be accurate. Early in the design phase of the flow meter it was imagined that a standard SST3010 DP with dual electrical connection head (one to topside, the other to a separate temperature subsea transmitter) would be utilized. However, design optimisation resulted in the SST3010 MV (as shown in Figure 4) with the same functionality in a head with integrated non-intrusive temperature probe. Whilst this solution would therefore require additional validation testing, it provides a unique and patented solution that integrates the whole instrumentation package in one contained unit, thus aiding manufacture and integration.

Table 1 gives a summary of the assessed differences in the TRL level between existing oil and gas meters (Dualstream and Seastream), and the Carbonstream. This highlights that whilst developing on the basis of similar products is useful, significant additional work is required to take a new design from concept to fully qualified. Subsequent to all components being at TRL 5, further TRL progress would require an Integration Test and Field Trial.

Table 1 - Comparison of TRL for Carbonstream at the start of the development project

Component	Existing Subsea Oil and Gas Meters	Carbonstream (start of development)
Meter Body and Flanges	TRL 7	TRL 5
SST 3010 DP	TRL 7	TRL 5
T transmitter adapted connection head	N/A	TRL 2
FloCalculator	TRL 4	TRL 4
EOS Software	N/A	TRL 2
Diaphragm Seals assembly	TRL 7	TRL 5
Electrical Connector	TRL 7	TRL 5
Support Frame	TRL 7	TRL 5

4 TESTING A NEW FLOW METER

The testing required for a flow metering system – and, in particular, a subsea flow meter – should provide extensive verification that it should continue to operate acceptably under the environmental and physical conditions that would be the extreme of what it may see in service. Continuing our example, Solartron ISA's design process includes a "Design Input and Review" form, which brings together a description of each function or requirement of the end product, the specification that it needs to meet, how the design will be verified, and how the design will be validated. Additionally, mandatory legal requirements, applicable codes and standards, and means of evaluating the reliability of the product are all detailed in a similar manner. Many of the verification and validation stages will be internal and external tests that need to be carried out and reported back.

Design Failure Mode and Effects Analysis (FMEA) considers and documents how the end product may fail in service and the effect this would have, whilst also looking at what mechanisms may have caused this problem. From this, the current design controls can be evaluated, and improvements prioritised.

For subsea systems, API 17F (currently in the fifth edition) [13] provides guidance on the testing requirements, including aspects like shock and vibration, temperature cycling, temperature soaking, and hyperbaric testing. The development from an existing SST design meant that much of the pressure containment assessments had already been carried out, as the primary and secondary containment of the new system is identical to the SST3010 DP. Accelerated life testing provides an additional means of assessing the reliability and durability of the electronics.

In all these tests, the purpose is to identify potential failure modes and design flaws before the meter ever goes into production and service. Whilst a successful test may provide a positive outcome, a negative test result that highlights an unexpected design issue may be considered to be equally good, as it prevents poorer performance down the line.

API 17F also details the management of component obsolescence, an aspect that was widely demonstrated during the impact the worldwide COVID crisis had upon supply chains, product availability, and the respective product life cycles. Where key components require change during the product life cycle, this has an immediate impact upon the TRL value until suitable testing and evaluation of the component and full system has been completed. Development and testing of flow meters, including the Carbonstream, therefore should where possible take this into account.

Once the first complete Carbonstream prototype was completed, an opportunity was taken to test the full system on the DNV Bishop Auckland Flow Loop [14]. This flow testing and flow calibration facility is connected to the UK natural gas grid and is able to provide up to 60 bar of pressure at flow rates up to 30 million standard meters cubed per day. It is also less than ten miles from the Solartron ISA facility at Shildon, County Durham, making it an ideal testing location.

Figure 5 - Carbonstream meter installed in ice bath at DNV Bishop Auckland

Solartron ISA designed a test where the meter was submerged in an insulated ice bath containing water and ice to cool the outside of the meter to values approximating those of typical seabed temperatures. Two different natural gas fluid temperatures were achieved at three different test point flow rates (each with five or more repeats), with initial flow rate performance of better than ±1.0% (which was further improved to better than ±0.5% once allowances for composition changes in the gas throughout the day, and temperature changes due to initially having insufficient ice in the box, were corrected for, see Figure 6). In this manner a complete systems test could be performed, utilizing natural gas as the flowing fluid, demonstrating this to a number of attending witnesses from oil and gas companies and the North Sea Transition Authority (NSTA).

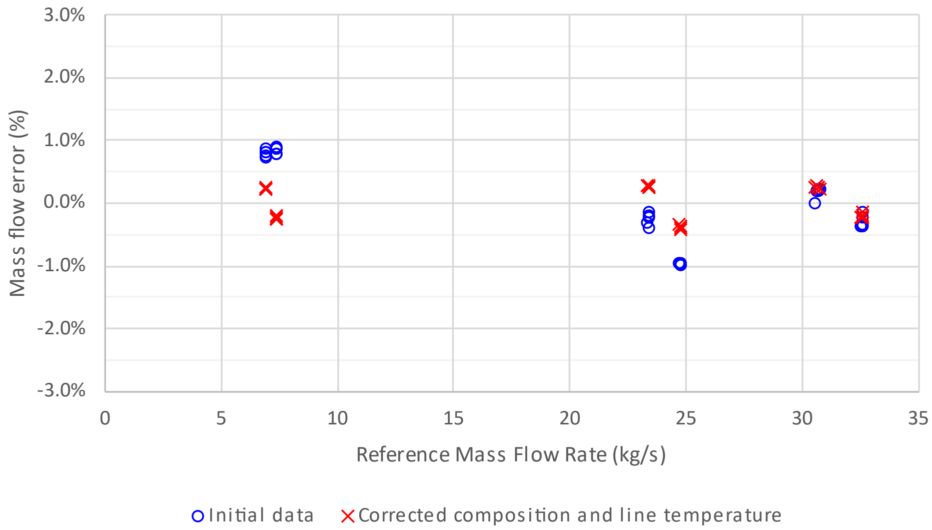


Figure 6 - Data from DNV Bishop Auckland test

Although the primary meter design for this application is subsea, there is no reason why a topside application would not be appropriate. Therefore, Solartron ISA agreed to participate in DNV's CO2MET JIP [15] at DNV Gronigen [16] in November 2023 (ambient) and March 2024 (cold test) for gaseous CCUS-appropriate fluids, as the limitations of their current flow loop meant that only gas state was available.

The Carbonstream meter, as shown in Figure 7, utilized topside instrumentation (including NIS temperature) and a Solartron ISA Hazardous Area Flow Computer with the same underlying software for flow calculations and EoS. Initial details of the project are being declared to the project partners, and a summary of the results presented at this flow measurement workshop. We are therefore not currently releasing our results from the CO2MET JIP; however, our overall performance was – as would be expected for single phase fluids and Venturi measurement – more than acceptable, with a small unintended bias due to the ambient temperature measurement in a flow loop setting. It is through projects like these that good comparison between different metering technologies can be carried out, and therefore should be supported across the developing industry.

4.1 Pressure Loss Ratio as a Diagnostic Tool

One additional aspect of the Carbonstream meter at DNV that can be seen in Figure 7 was the use of an additional tapping and DP measurement on the meter. As the Venturi included a third tapping as per our Dualstream range of meters (with the tapping located at the end of the divergent cone), it was decided to evaluate the performance of the pressure loss ratio (PLR) in these CO2-dominated fluids. In the Dualstream meters, this measurement of the DP across the whole meter is ratioed by the measured Venturi DP to give the PLR, and this can be used to indicate (and, with enough data, to quantify) the presence of liquids flowing through the meter, as the Solartron ISA PLR is particularly sensitive to even very small quantities of liquid.

Figure 7 - "Topside" Carbonstream mounted in DNV Groningen loop for CO2MET JIP

For most of the JIP test no liquid was present, and the PLR has a roughly constant value as expected. However, at some point in the tests an adverse condition occurred where the Carbonstream meter saw the PLR rise (see Figure 9); these flows were later excluded from the main part of the JIP by DNV as liquid is thought to have been present, due to condensation within the reference metering system. Note that this multiphase situation was not initially indicated by the Equations of State in use at the time, which should be considered by all CCS operators. Solartron ISA are therefore considering the additional use of PLR on the Carbonstream meters as a diagnostic tool, as although the presence of liquid in supposedly single-phase CCS flows is unplanned, being forewarned to this may be useful where other flow metering technologies may be adversely affected. (Note that Venturi meters are used extensively in multiphase and wet gas flow, and so if the amount of liquid present can be determined, a correction can likely be applied to the "single phase" flow rates.)

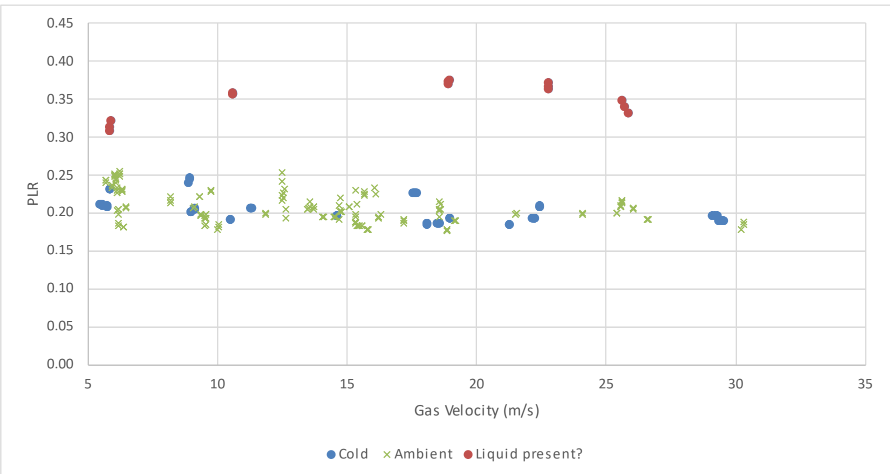


Figure 8 – Pressure Loss Ratio (PLR) indicating likely presence of liquid

4.2 Publicity

Whilst detailed testing of a new flow meter design is necessary, it is also important to keep considering how the range of potential users may expand over time. Particularly in CCS, more people are entering into this area to try and engineer and purchase appropriate solutions. Therefore, attending suitable conferences and trade shows can be of assistance. Although the model shown in Figure 4 is not a real Carbonstream meter, it is a 1:1 scale of such a device and can facilitate excellent discussion.

Figure 9 - Carbonstream model being exhibited at CCS Expo, Houston

5 METERS IN SERVICE

Although CCS has been in existence since the 1920s, the first large scale project did not occur until 1996 with Sleipner and Snøhvit (2008) in Norway at up to 1.8 Mtpa, resulting in storage of over 25 Mt since commissioning. It is notable that these two projects and numerous other small-scale projects, accounting for approximately 300 Mt CO2 stored to date, have been developed by a single organization. This means that all the risks and costs sit with that one developer. With the emergence of the CCUS hubs with the sharing of risks and costs, we are now seeing the need to accurately account for the CO2 and attribute those costs accordingly. This in turn has led to a focus on CO2 measurement and the level of acceptable accuracy.

The Northern Lights Project is at the forefront of managing this step change in project complexity and have identified the need to accurately measure the CO2 at the final point of injection at the well with single phase flow meters. Solartron ISA have been privileged to supply these meters and look forward to gaining experience once the project is operational.

Figure 10 - Northern Lights meter (black and white picture)

6 UNCERTAINTY OF UNCERTAINTY

Whilst all parties want the most accurate flow measurement possible (for a reasonable price point), the determination of what should be considered acceptable has proven so far to be non-trivial. The uncertainty required for flow metering of CCUS fluids can involve both the metering technology uncertainty and Equation of State uncertainty, the latter being particularly important for those metering technologies that do not directly calculate a mass flow rate.

TUV NEL's paper in 2011 [17] states that "Under the EU ETS, the mass of annually transferred CO2 is required to be determined within a maximum uncertainty of less than 1.5%". The calculation of density from measurements of pressure and temperature, with sampling of the fluids for the Equation of State (EoS) are also recognised, as are the need for validation of metering systems in rich CO2 mixtures.

The NORCE paper at the 2020 North Sea Flow Measurement Workshop [18] noted that "For the application area investigated in this paper, the maximum relative uncertainty for measurement of CO2 mass flow measurements is ±2.5%. Depending on when full scale storage sites become operational, and when new technology becomes available, National regulations may be updated."

A more recent paper [19] indicates that this ±2.5% level applies to the most accurate Tier 4 systems, and depending on the metering technology, both the measurement uncertainty and the gas composition analyser need to be considered, "For example, if the uncertainty of each component is approximately 1.75%, this would deliver a combined uncertainty of 2.5% for CO2 flowrate." (i.e. square root of the sum of the squares of each part).

In terms of CCS projects, for the purpose of examples, one project requires an uncertainty of ±3%; another that "the overall uncertainty on mass CO2 shall not exceed 1.5%...for capacity lower than 10% of the maximum capacity… the overall uncertainty on mass CO2 shall not exceed 3%".

Note that the North Sea Transition Authorities document [20] states: "The UK-ETS generally requires a measurement uncertainty of less than ±2.5% in mass of CO2 , but it is envisaged that for commercial CCUS applications, the uncertainty requirement may be ±1.5% (mass of

CO_2 ; i.e. including the uncertainty in determining the proportion of CO_2 in the rich fluid via sampling and analysis) or less."

The EoS equations applicable to CCUS – for instance, see the review [21] - typically include standard cubic EoS (for which there is often insufficient data to appropriately characterise for CCUS applications), GERG-2008 [10] (which isn't optimised for CCUS applications, but appears to work adequately), and EOS-CG [22] and similar developments [23], which are looking to provide CCUS-specific equations (but provide only limited accuracy improvements and less generality when compared to GERG-2008).

In terms of EoS accuracy, this is more difficult to detail. For instance, if GERG-2008 is taken at face value it states an uncertainty in density of ±0.1%. However, typical CCUS compositions are outside of the bounds stated in this document; therefore, additional data is required to evaluate how well EoS work outside of their nominal bounds. This is where projects such as the DNV CO2MET JIP [15] are vital, as they provide experimental evidence of the actual uncertainty, and show that the aforementioned EoS may be accurate enough for the total mass flow rate uncertainty requirements of current projects. Further improvements in CCUS-specific EoS will only serve to improve this situation.

It is also important to consider adverse conditions scenarios that are not currently considered within project specifications. This was clearly illustrated earlier by the CO2MET JIP, where two-phase CO_2 flow has been unexpectedly created, causing adverse effects in other metering systems, and a noticeable PLR signal from a Venturi meter. Although systems may be planned to be operated in single phase, it is sensible to learn as much as possible from the types of flow assurance issues seen within the oil and gas metering systems operated over many decades. More detailed multiphase CO_2 EoS may prove a useful addition for future operation of CCUS systems.

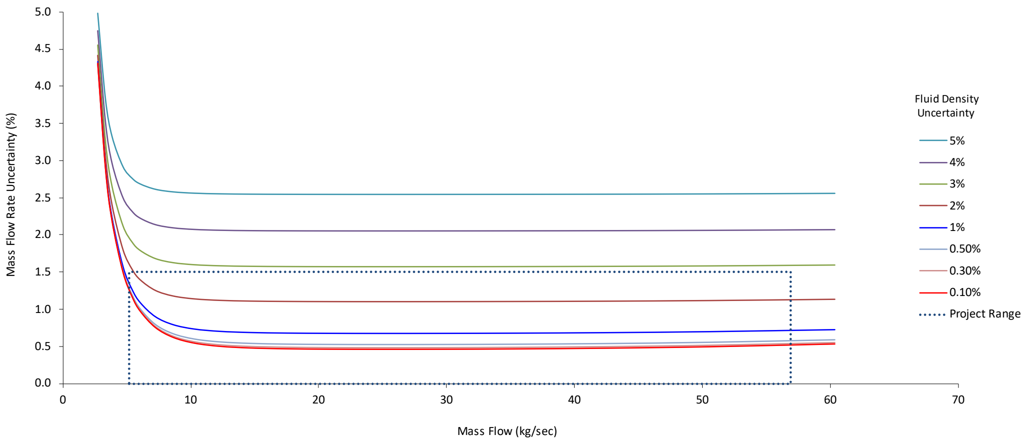
The purpose of these previous paragraphs is to illustrate that there is not a single value for the acceptable uncertainty for CCUS applications. However, this is also true of oil and gas systems, where even with the NSTA guidance [24] recognises that, for example for wet gas flow meters: "The uncertainties that can be achieved by wet gas meters are typically application-dependent and may not always be quantifiable." Therefore, as the title of this paper is meant to humorously point out, there is a lack of certainty in what uncertainty should be acceptable for the metering technology itself.

6.1 Uncertainty Examples

With a number of projects now able to provide some data for sizing of flow meters, initial calculations of mass flow rate uncertainty can be evaluated, as per Figure 11.

These two examples provide for a given set of operating pressure and temperature, composition, and mass flow rates, a guide to the required uncertainty in fluid density to meet a target project uncertainty specification (which has been assumed to be ±1.5% for the purposes of this paper) for a Venturi-based flow meter. Due to the Venturi equation for mass flow rate being proportional to the square root of the density, the fluid density therefore would have to be known better than ±3% to meet the project specification. For these examples, if the fluid density is known better than ±2%, the mass flow rate would meet project specifications, even at lower mass flow rates with their corresponding lower differential pressures (which would have higher instrumentation uncertainty).

It has already been noted that GERG-2008 [10] states a density uncertainty of ±0.1% (hence the lowest line in the graphs), but that this does not currently include typical CCUS compositions. Assuming a project composition of greater than 95% CO_2, the uncertainty in the fluid density is likely to be a small multiple of this value, which although unknown would therefore still be likely meet the project requirements across the full range of project operations.



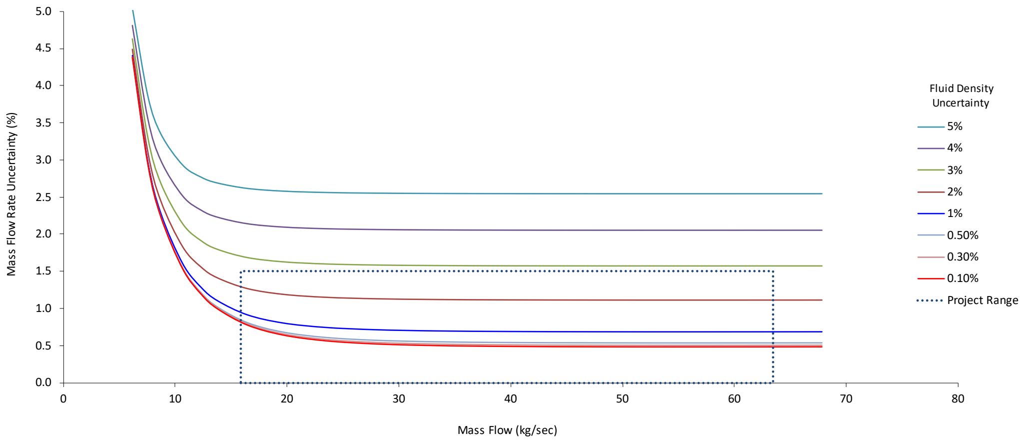


Figure 11 - Two examples of Venturi mass flow rate uncertainty for different fluid density uncertainties (User target mass flow uncertainty assumed to be ±1.5%)

For single-phase flow metering the ISO 5168 [26] standard already provides details on how to evaluate the uncertainty of such a system. Note that this includes the use of an Uncertainty Budget (as per the example in Figure 12) and the calculation of sensitivity coefficients in each relevant parameter. This method can assist in evaluating the respective importance of the uncertainty in each parameter to the overall flow rate uncertainty at a given set of input conditions. Whilst this may not provide a single overall flow rate uncertainty for the project, it can indicate the regions where meeting a target specification is likely to require more attention.

Description	Symbol	Units	Nominal Value	Expanded Uncertainty (%)	Probability Distribution		Standard Uncertainty	Sensitivity Coefficient	Contribution To Overall Uncertainty
Discharge Coefficient	C	-	1.002	0.40	Normal	2.00	0.20	0.8604	0.17209
Venturi Throat Diameter	d	*mm*	53.44	0.1	Normal	2.00	0.05	2.0956	0.10478
Pipe Diameter	D	*mm*	124.38	0.4	Normal	2.00	0.20	-0.0547	-0.01094
Fluid Density	ρ	*kg/m3*	846.193	0.5	Normal	2.00	0.25	0.4353	0.10881
Differential Pressure, (mbar)	ΔP	*mbar*	40.0	3.486	Normal	2.00	1.74	0.4353	0.75864
Isentropic Exponent	κ	-	23.5450	1	Normal	2.00	0.50	0.0000	0.00001
Viscosity	μ	*cP*	0.01537	10	Normal	2.00	5.00	-0.0090	-0.04494
Pressure	P	*bar(a)*	80.000	1	Normal	2.00	0.50	0.0521	0.02607
Temperature	T	*DegC*	7.000	1	Normal	2.00	0.50	0.3169	0.15846
Coefficient of Thermal Expansion	TE	-	0.0000117	1	Normal	2.00	0.50	-0.0003	-0.00013
Reference Temperature	T_ref	*DegC*	20	1	Normal	2.00	0.50	-0.0004	-0.00020
CO2 composition	-	*mol% (abs)*	95.2384%	1	Normal	2.00	0.50	0.0400	0.02000
								Standard Uncertainty	0.81
								Expanded Uncertainty (95%)	1.62

Figure 12 - Example Uncertainty Budget for CCUS Venturi meter

With tools such as these, the evaluation of uncertainty is certainly possible for given conditions and with appropriate data. However, this also relies on knowing how well each component is known – and once again this may highlight the current lack of certainty with regards to the PVT EoS calculations. Other parameters – including how well a chromatograph is able to determine each component in a CCUS application – also require consideration. We fully expect further development in CCUS-specific EoS and uncertainty calculations in future years.

7 FORWARD TO THE FUTURE

With the current yearly trend in atmospheric CO2 only increasing, CCS will continue to be an important area for development in the next few decades. As such, the development of CCS flow meters – for both subsea and topside applications – will be an important area to get right. With Oil and Gas, flow meters were often titled the cash registers of the industry, as all metered product had an intrinsic worth. Whilst CO2 Emissions Trading Schemes assign a monetary value to the metered fluids, we need to ensure that “ignorance is bliss” does not apply to CCS flow meters.

As has been illustrated, there are key standards to assist in the development process for flow meters for CCS. Along with the developing commercial and governmental guidelines for CCUS operations, fluids transportation, and storage, the future of carbon capture and storage metering is assuredly on a less uncertain footing.

Whilst metering may provide a key property in managing CCUS applications, flow rate uncertainty is also key. Therefore, ongoing improvements in this area should continue, as it is more imperative for “last known good” measurements to be well known. Current EoS calculations already provide sufficiently good uncertainty for metering technologies that do not directly calculate mass flow. However, uncertainty in CCUS-specific fluids using PVT EoS calculations should also continue to be investigated, and where possible, updated.

With over 110 storage hubs in development across the world with a storage capacity of 280 Mtpa by 2030, the development of measurement technologies will accelerate as these project more through their development phases. The marginal nature on the Carbon Capture and Storage value chain means that regulators, emitters and transport/storage companies will need a common (and peer group accepted) benchmark for measuring the CO2 being transported and stored. This project along with many others will hopefully help to develop this required common understanding.

8 NOTATION AND ABREVIATIONS

CCS	Carbon Capture and Storage
CCUS	Carbon Caputure, Utilization and Storage
CDR	Carbon Dioxide Removal
CO2	Carbon Dioxide (i.e. its chemical formula)
EoS	Equation of State
DP	Differential Pressure
Gt	Giga-tonnes, i.e. 10^{12} kg
Gtpa	Giga-tonnes per annum
JIP	Joint Industry Project
Mtpa	Mega-tonnes per annum
NIS	Non-Intrusive Sensor
NSTA	North Sea Transition Authority
PIDOV	Plan, Identify, Design, Optimise, Validate
PLR	Pressure Loss Ratio, the ratio of the total DP across a Venturi to the DP from the upstream to the throat
PVT	Pressure, Volume, Temperature (typically with reference to EoS calculations)
SST	Subsea Transmitter
TRL	Technology Readiness Level
VoC	Voice of the Customer

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