Flow Measurement in Support of Carbon Capture, Utilisation and Storage (CCUS)

National Engineering Laboratory

Add value.
Inspire trust.

A horizon scan conducted by TÜV SÜD National Engineering Laboratory for the Flow Measurement Special Interest Group of the Institute of Measurement and Control

Dr Chris Mills

Date: September 2021

Report No: 2021_299
Project No: FQKT11

EXECUTIVE SUMMARY

Carbon Capture, Utilisation and Storage (CCUS) is a key United Kingdom (UK) government strategy for reducing carbon dioxide (CO_2) emissions in order to combat the potentially catastrophic effects of climate change. It is a cornerstone of the UK's Green Industrial Revolution [1]. The UK aims to capture and store 10 million tonnes of CO_2 each year by 2030 [2]. Ensuring this target is achieved will require a clear strategy, regulations, guidelines, and funding from government. A full UK government road map will be published in late 2021 that will provide details on available funding and guidelines for high CO_2 emitters [2].

Across the entire CCUS value chain, all of the stages require accurate measurement of CO_2 at temperatures, pressures, flow rates and fluid phases that can be validated through a credible traceability chain for flow. This traceability chain will provide the confidence in meter performance, financial and fiscal transactions and, critically, environmental compliance. It is understood that the UK adopted version of the EU Emissions Trading System will specify an uncertainty value for carbon dioxide flow measurement that must be adhered to [3] [4]. Accordingly, the provision of accurate and traceable flow measurement of CO_2 in the UK will be essential for the successful operation of CCUS.

Carbon dioxide has unique fluid property behaviour that presents several measurement problems. In particular, the transitions between fluid phases are close together and fall within typical process conditions for transportation. This means that throughout the CCUS chain, the CO_2 could potentially be single-phase liquid, single phase gas, two-phase liquid and gas, or supercritical fluid. These challenges must be met to ensure the accurate measurement of CO_2 throughout the CCUS value chain.

At present, across the globe, there are no CO_2 flow measurement facilities capable of traceable flow calibrations of gas phase, liquid/dense phase and supercritical phase CO_2 that replicate real-world CCUS conditions. This is a significant barrier for the successful implementation of CCUS projects worldwide not least because these will be governed by Legislation and Environmental Regulations requiring traceable measurement. Accordingly, substantial research is required, together with investment in state-of-the-art flow measurement facilities for gas phase, liquid/dense phase, and supercritical CO_2. Essential steps towards a credible, regulated CCUS regime include:

- a traceable CO_2 gas flow measurement facility that replicates the conditions experienced within the CCUS value chain, with a resulting national flow measurement standard
- a traceable CO_2 liquid/dense flow measurement facility that replicates the conditions experienced within the CCUS value chain, with a resulting national flow measurement standard
- a traceable CO_2 supercritical flow measurement facility that replicates the conditions experienced within the CCUS value chain, with a resulting national flow measurement standard

The absence of traceable CO_2 gas and liquid flow measurement facilities and accompanying national or international flow measurement standards will seriously impede the widespread deployment of CCUS. There are a number of possible options for dealing with the situation outlined. These include direct UK Government investment in facilities and research, collaboration with overseas National Flow Laboratories, and cooperation with international research bodies such as EURAMET. However, consideration of these options falls outside this review. We therefore recommend that the Institute of Measurement & Control (InstMC) considers our evidence with respect to CO_2 gas and liquid flow and CO_2 supercritical flow and advises Ministers and relevant third parties accordingly.

Abbreviations	
API	American Petroleum Institute
BEIS	Department for Business, Energy & Industrial Strategy
CAD	Computed Aided Drawing
CCUS	Carbon Capture, Utilisation and Storage
CFVN	Critical Flow Venturi Nozzles
CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Designated Institute
DP	Differential Pressure
DS	Documentary Standards
EMCF	Exhaust Meter Calibration Facility
EOR	Enhanced Oil Recovery
EoS	Equations of State
ETS	Emissions Trading Scheme
EU	European Union
FEED	Front-End Engineering Design
Gt	Gigatons
H_2O	Water
H_2S	Hydrogen sulphide
IEA	International Energy Agency
InstMC	Institute of Measurement & Control
ISO	International Standards Organization
LNG	Liquified Natural Gas
NEL	TÜV SÜD National Engineering Laboratory
NIST	National Institute of Standards and Technology
NMS	National Measurement System
NO_2	Nitrogen dioxide
PHMSA	Pipeline and Hazardous Materials Safety Administration
SO_2	Sulphur dioxide
UK	United Kingdom
USA	United States of America

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

The Flow Measurement Special Interest Group (henceforth known as FMSIG) of the Institute of Measurement and Control (InstMC) noted the key prominence of Carbon Capture, Utilisation and Storage (CCUS) within the UK Government's 'Energy White Paper: Powering our net zero future' [5]. Given how central CCUS is to the Government's Decarbonisation Strategy, FMSIG was concerned that there may be considerable gaps in the requisite flow measurement capability (knowledge, techniques and supporting infrastructure) that could significantly impede wide-scale deployment of CCUS technologies to achieve that strategy. Accordingly, FMSIG recommended that the UK's Designated Institute (DI) for Flow Measurement, TÜV SÜD National Engineering Laboratory (NEL), should provide a comprehensive independent review of CCUS measurement requirements and the current standing.

With fossil fuels still providing more than half of the world's energy needs, Carbon Capture, Utilisation and Storage is seen as being crucial in reducing anthropogenic carbon dioxide emissions as part of a secure and sustainable global energy supply [6] [7]. According to the International Energy Agency (IEA), world energy-related CO_2 emissions were approximately 33 gigatons (Gt) in 2019 [8]. At the same time, it has been estimated that the UK sector of the North Sea has sufficient capacity to store around 78 Gt of CO_2 in saline aquifers [9]. Based on the UK's 2019 CO_2 emissions, this corresponds to over 200 years of capacity. It is clear that CCUS will play a fundamental role in combating climate change and will help Paris agreement signatories meet their legally binding greenhouse gas reduction targets [10]. Reaching net-zero emissions will be virtually impossible without CCUS [11]. By successfully implementing CCUS projects, the world could reduce CO_2 emissions by 25 % by 2050 [12].

Carbon Capture, Utilisation and Storage is presented as key in the UK's Government's 'Energy White Paper: Powering our net zero future' [5]. As part of its industrial decarbonisation strategy, the UK government has committed to deploy two CCUS clusters by mid-2020s and a further two by 2030 [1]. However, significant gaps exist in the requisite flow measurement capability that could significantly delay the utilisation of CCUS technologies.

Eradicating all anthropogenic carbon dioxide (CO_2) emissions is clearly not an option. Most scenarios (88 out of 90) envisaged by the IPCC rely on carbon removal technologies to compensate for residual emissions which cannot be avoided or abated, and to reduce the amount of CO_2 in the atmosphere to acceptable levels [13]. CCUS is the only solution that can deliver negative emissions at large scale. Put simply, many key industrial processes will not be able to achieve net zero emissions without implementing CCUS. For example, the production of cement emits significant levels of CO_2 as a by-product during the process of heating limestone and breaking it down into calcium oxide [14].

CCUS will be crucial in providing negative emissions directly through Direct-Air-Capture (DAC) and indirectly through deploying BioEnergy with Carbon Capture & Storage (BECCS) [15]. These negative emissions technologies (NETs) offer considerable capacity for reducing CO_2 emissions further and faster than relying solely on decarbonising the energy sector and hard-to-abate sectors (e.g., steel, chemical).

The UK Government has also recently launched a 'UK hydrogen strategy' that aims to develop "*a thriving low carbon hydrogen sector in the UK*" [16]. CCUS will be central in supporting the rapid upscaling of low-carbon hydrogen production via steam methane reforming [17]. Methane reforming with CCUS provides a clear pathway for the low-cost generation of hydrogen and will be fundamental in the UK's hydrogen strategy.

Overall, CCUS will be critical to reduce global CO_2 emissions, both by providing negative emissions and by supporting scaled up hydrogen production. It is essential that all captured CO_2 be accurately measured across each stage of the CCUS chain. This is necessary for process control, for environmental monitoring (e.g., detecting CO_2 leakage), and for verification of the CO_2 quantity accounted under emission schemes.

Traceable flow measurement will be required at various stages across the CCUS chain to accurately track the captured CO_2 from emission source through to either utilisation or sequestration. Particular steps requiring traceable measurement include CO_2 capture from emitters, custody transfer across the CCUS chain, and CO_2 utilisation or storage. Such measurement will further ensure fugitive loses are kept to a minimum, safety protocols are followed, and that the CO_2 is maintained in the ideal fluid phase to optimise the CCUS process. At each stage, accurate measurement is required, despite varying temperature, pressure and fluid phase. Hence, while flow metering may not represent a significant cost element in the CCUS chain, it will be a critical component, as the technical performance, financial transactions and environmental compliance will all require accurate flow measurement data.

Understanding, monitoring, and controlling the flow rate of CO_2 will be essential for the viable operation of CCUS in the UK. This will require a clear understanding of temperature, pressure, and phase behaviour, impurity levels, as well as the selection of appropriate flow measurement technology and ensuring that it performs correctly.

To achieve the UK adopted version of the EU Emissions Trading System measurement uncertainty value, a dedicated national measurement infrastructure that includes gas and dense liquid CO_2 will be required [3] [4]. At present, a traceability chain for CCUS does not exist. There is no accredited flow calibration facility in the world that uses CO_2 as the fluid medium that can fully replicate CCUS conditions. Meanwhile, flow traceability will play a vital role in the UK's national infrastructure since accurate measurements of CO_2 and confidence in the recorded data will be impossible to achieve without it. This CO_2 flow traceability will be the technical proof that a flow measurement device has the appropriate measurement chain referenced back to the UK national measurement standard. In the UK, the system for national measurement standards is known as the National Measurement System (NMS), which is delivered through the UK Government's Department for Business, Energy & Industrial Strategy (BEIS). Such standards underpin a whole host of key areas such as Regulations, Trade, Consumer Confidence, International Treaties, and Environmental protection measures.

1.2 Objectives

This review of flow measurement in support of Carbon Capture, Utilisation and Storage (CCUS) explores three main areas:

- Evidence-based documentation of the role flow measurement will play in enabling CCUS by underpinning trade, consumer protection and confidence, taxation, health and safety, environmental protection, and treaty obligations.
- Assessment of the current CCUS traceability chain in UK and other leading nations.
- Assessment of the required future UK CCUS traceability chain.

The review also considers how flow measurement requirements vary between the various modes of the CCUS lifecycle (Capture, Transportation and Storage) and how CO_2 presents specific measurement challenges.

1.2 Methodology

This report draws together evidence in the available literature on CCUS flow measurement practice from journals, articles, conference papers and measurement industry standards as well as from discussions with relevant stakeholders.

1.3 Outline of the report

Section 1 outlines the background of the project and Section 2 provides the findings. Section 3 summarises the review, whilst Section 4 provides recommendations.

2. FINDINGS

The challenges presented by the physical properties of CO_2 are discussed in Section 2.1. The role of flow measurement in enabling CCUS and specific flow meter technologies for CCUS are detailed in Sections 2.2 and 2.3 respectively. Section 2.4 presents the requirements for and the current status of the CCUS traceability chain in the UK, Europe and internationally. Sections 2.5 and 2.6 cover Regulations and Documentary Standards respectively. Section 2.7 presents the future needs.

2.1 Measurement Challenges arising from the Physical Properties of CO_2

The unique fluid properties of carbon dioxide present several measurement challenges. CO_2 is in a gaseous state at ambient temperature and pressure (e.g., 1 bar and 20 °C). However, it readily liquifies, for example at around 57 bar and 20 °C it enters the liquid phase. Above the critical point of 31.1 °C and 73.9 bar, CO_2 becomes supercritical i.e., it exhibits properties which are hybrid between gas and liquid. As 31.1 °C is close to ambient temperature, CCUS operations may easily approach the critical point. Operating near the critical point can present significant technical challenges for process control and measurement as small changes in temperature and pressure can cause large changes in fluid properties (e.g., density).

Several measurement problems arise in the CCUS chain, some from the special characteristics of CO_2 and others from the process conditions used in CCUS applications [18] [19]. CO_2 has been successfully measured in emission monitoring schemes [3] for decades, where the CO_2 is usually in the form of a low pressure and low temperature gas. While there remain significant traceability challenges for CO_2 in these conditions, they are at least conducive to good measurement practices. For example, constructing a traceable CO_2 gas flow facility for low pressure (1 bar to 10 bar) and low temperature (20 °C to 40 °C) would be simpler than one at elevated pressures (> 40 bar) and extreme temperatures (both sub-zero and > 60 °C).

One unusual feature of the physical properties of CO_2 is that the boundaries dictating fluid phase transitions are close together and lie near to ambient conditions. The phase diagram for CO_2 and the "CCUS Operating Range" (highlighted in yellow) for measurement in the CCUS chain are shown in Figure 1.

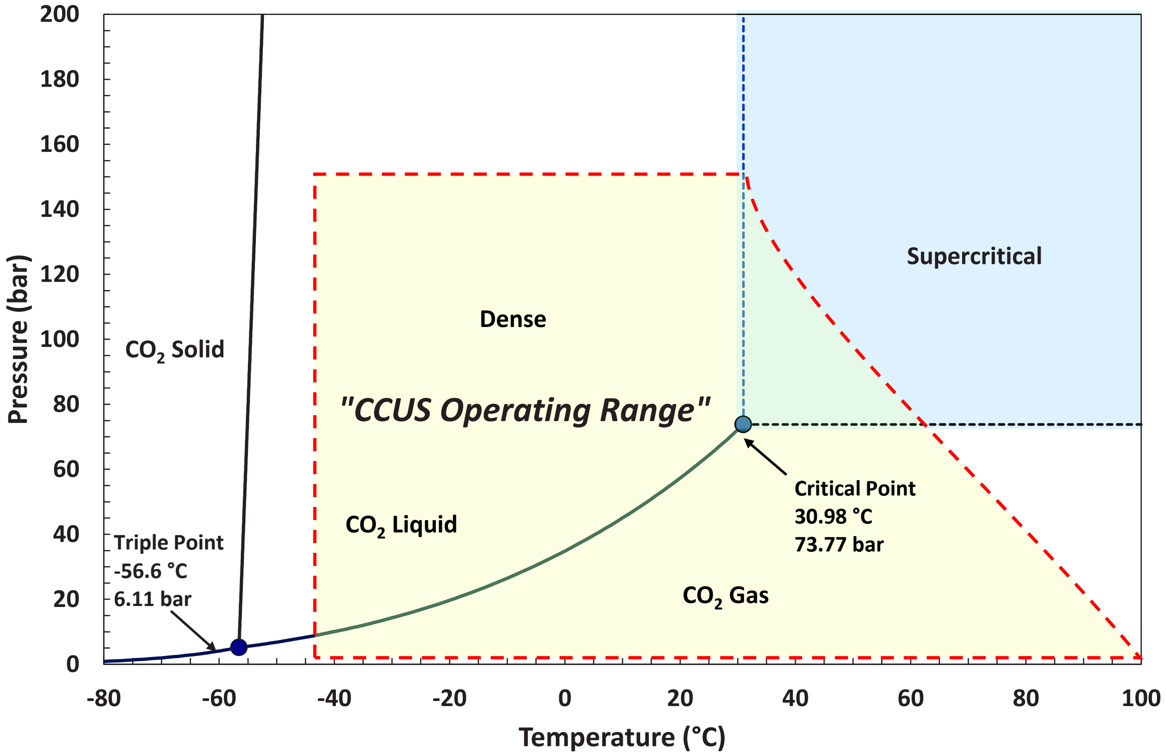

FIGURE 1 PURE CO_2 PHASE DIAGRAM ("CCUS OPERATING RANGE" HIGHLIGHTED IN YELLOW)

Within the operating region of the CCUS chain, CO_2 can be single-phase liquid, single phase gas, two-phase liquid and gas, or supercritical fluid. All four potential phases present different measurement challenges [20] [21] [22]. Furthermore, as the phase boundaries lie close together, maintaining the desired fluid phase can be challenging [23] [24]. This is particularly the case for transportation across large pipe networks. Regulating the temperature and pressure over pipelines that span hundreds of miles is difficult, where, for example, varying climates and elevation may alter the ambient temperature and pressure.

Whilst materials such as nitrogen, natural gas, oil, and water are safely transported across entire continents by trucks, pipelines and even ships, the unique phase behaviour of CO_2 presents significant challenges. Oil and water for example are transported at pressures and temperatures well below their respective critical points, whereas nitrogen and methane are transported at conditions well above their critical points [24] [25], and hence there is minimal risk of phase changes.

The possibility of phase change is further exacerbated by the likelihood of impurities present in the CO_2. Depending on their type and concentration, impurities may cause significant shifts in phase boundaries, the critical point, and specifically the two-phase region. Impurities may create two-phase flow at process conditions that would be single-phase gas or single-phase liquid for pure CO_2. For example, Figure 2 shows the shift in the gas-liquid transition region for a mixture of CO_2 and hydrogen (H_2) with varying hydrogen concentration.

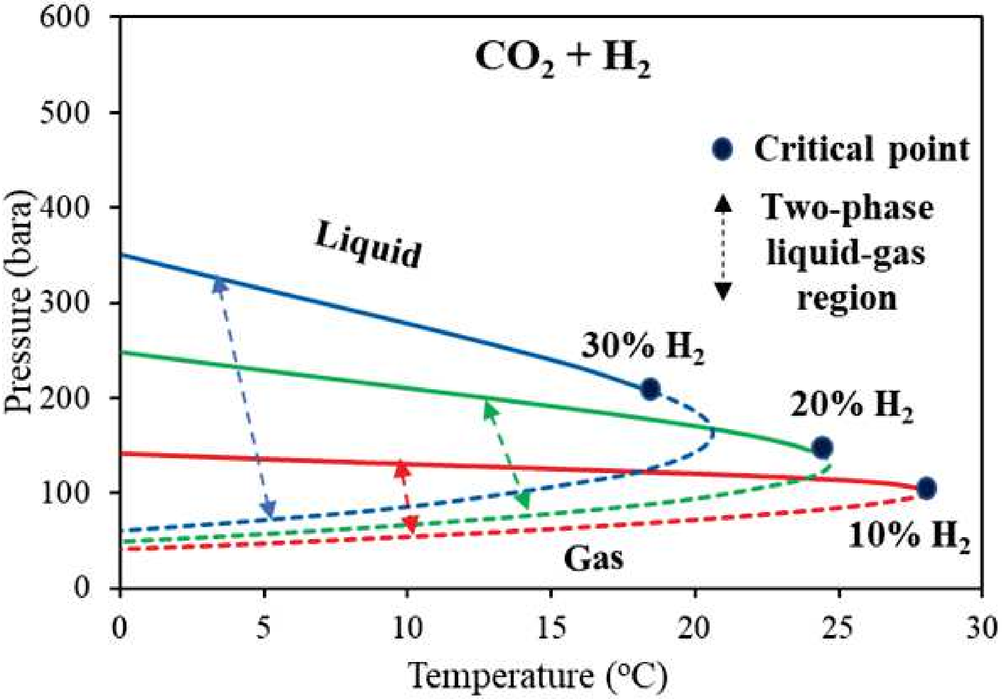

FIGURE 2 PHASE DIAGRAM OF CO_2/H_2 MIXTURE WITH VARYING H_2 CONCENTRATION

As a result of the CO_2 phase envelope, small variations in temperature and pressure can lead to rapid and substantial changes in the fluid phase of CO_2. This presents a significant challenge to flow metering, as meters are generally designed to operate in a single phase, either liquid or gas [21]. Accordingly, appropriate flow metering technology and installed location will be required to ensure that the phase condition is predictable and controllable. This may necessitate the use of gas meters at certain locations and liquid meters at other locations along the network. The measurement of two-phase flow is challenging; most single-phase flow meters do not measure accurately in the presence of a secondary phase [26]. As well as flow changes affecting the accuracy of meters, in some cases a change of conditions and phases may also cause irreversible damage to the meters [27]. For example, devices with moving parts are unlikely to be suitable for CO_2 applications.

One of the biggest challenges for accurate measurement will be determining the exact properties of the CO_2 stream, due to variations in composition across the CCUS chain. These properties include density, viscosity, compressibility, and the speed of sound. For a 100 % pure CO_2 stream, the standard CO_2 phase diagram, and equations of state (EoS) may be relied upon to provide accurate data. However, a CCUS process stream is unlikely to be pure CO_2 as this could only be generated using a highly uneconomic process [28]. Accordingly, the pure CO_2 phase diagram and equations of state cannot be relied upon for industrial CCUS streams.

Traces of impurities such as NO_x, SO_x, N_2, H_2S, H_2O, and CH_4 have a large influence on the density and compressibility of the process stream [29]. The change in property values are functions of the component mixture and quantity. Thus, CO_2 streams across the CCUS chain will require substantial modelling to determine their true phase envelope, together with regular sampling to determine the actual fluid composition, in order to ensure the correct operating conditions are maintained [30]. Consideration of the likely variation and impact of stream composition will be required at the Front-End Engineering Design (FEED) stage to ensure the correct type and location of flow meters are selected, along with appropriate operation and maintenance schedules for these devices. It will also be essential to validate the accuracy of fluid density calculations, based on the stream composition and other measurements, which is used to derive mass[1] flow data.

There has been a reasonable amount of research investigating the effects of impurities in CO_2 streams [18] [31] [30] [32] [29] [33] [34]. Although some modelling and analysis of CO_2 has been carried out over the past two decades for the purpose of evaluating the transportation needs in CCUS schemes, they do not cover all scenarios and all combinations of impurities. Physical property software modelling packages can be used to generate fluid property data for the different CO_2 mixtures. However, these models will require validation to ensure they are accurate.

Another measurement challenge presented by CO_2 is that it exhibits acoustic attenuation, which may impact ultrasonic flow meter technologies [35]. Whilst this phenomenon is more significant in gaseous CO_2, it has also proved problematic in liquid CO_2 [36]. CO_2 exhibits acoustic attenuation due to a molecular relaxation process [37], arising from an exchange of energy between molecular vibrations and translations. This attenuation may cause an ultrasonic meter to lose the signal between its ultrasound transmitters and receivers. The effect is more significant at lower pressure. A reduction in the ultrasound signal will impact the measurement resolution and may have a detrimental effect on accuracy. This attenuation occurs at a specific frequency, which depends on the stream composition, density, phase, temperature, and pressure. Further research into thermal relaxation and its effect on CO_2 and flow metering technologies is required.

Any free water within the process stream could potentially result in the formation of highly corrosive carbonic acid and of hydrates that could seriously affect flow assurance and pipeline integrity [38]. This will present significant measurement challenges, including the potential requirement for water content to be monitored at all stages of the process to keep it below safe thresholds.

2.2 The Role of Flow Measurement in Enabling CCUS

It is essential that all captured CO_2 is accurately measured across each stage of the CCUS value chain. This is necessary for process control, to detect CO_2 leaks, and for verification of the CO_2 quantity accounted under any emissions scheme. Flow measurement will play a crucial role underpinning trade, consumer protection and confidence, taxation, health and safety, environmental protection, and treaty obligations. It is envisioned that the target measurement uncertainty for the UK adopted version of the EU Emissions Trading System will be ± 2.5 % (k=2) [3] [4]. However, this is still to be confirmed.

In essence, by accurately measuring the flow of CO_2 at each point of the process, a mass balance approach could be used to calculate the overall fugitive losses. In the simplest form, the mass balance approach calculates the difference between the amount of CO_2 transported away from the installation and the amount of CO_2 produced at the installation. The mass balance approach may also be used to identify for any losses across the network up to the injection wellhead. Unfortunately, this “by difference” approach requires extremely accurate meters, unless the losses are very high. To detect small losses based on only two measurements carried out at different locations would be extremely challenging.

With this in mind, there will be a requirement to meter the flow rate and determine the composition of CO_2 at multiple locations within the CCUS transportation network. In the UK, the exact locations along the transportation chain are still to be agreed, but several options are being explored. Figure 3 displays possible measurement nodes along the CCUS transportation network. These measurement nodes are denoted in the diagram as either purple or turquoise circles with a white “M”. The “transportation” measurement nodes are denoted as turquoise circles.

---

[1] The conversion of volume flow to mass flow for volumetric flow meters requires accurate density measurement data. Note that while most types of flow meter measure volumetric flow, mass flow (and hence totalised mass) is required for carbon auditing.

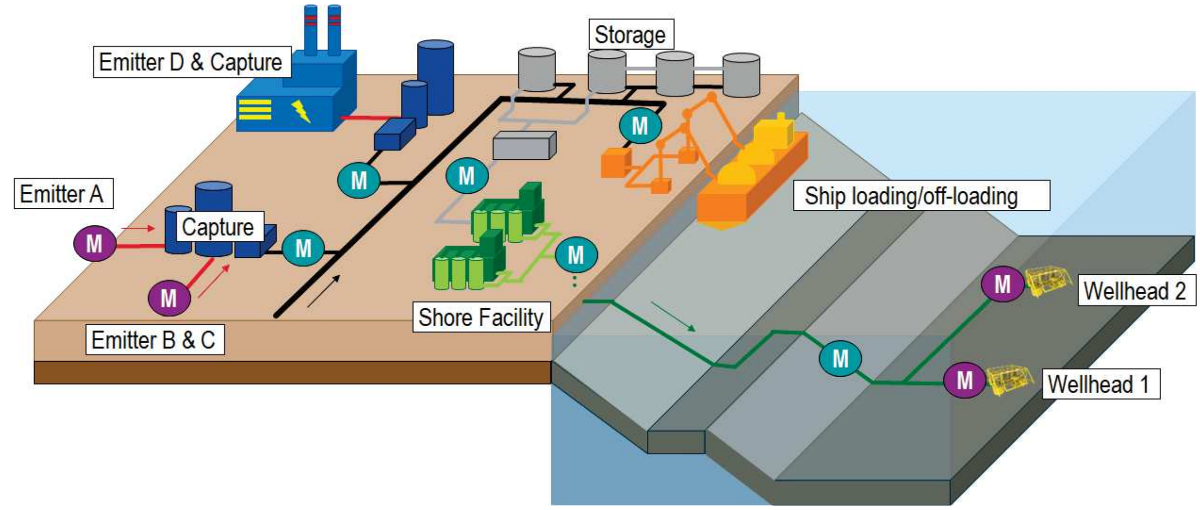

FIGURE 3 CCUS TRANSPORTATION MEASUREMENT NODES

The flow metering requirements will depend upon the specified measurement uncertainty, the fluid phase, the transportation method, and the regulatory requirements, but it is envisioned that measurement nodes could be installed at the following locations:

- The outlet of the emission source (e.g., coal fired plant)
- The inlet and outlet of the CO_2 capture facility
- At regular points within the CCUS transport network (e.g., at pumping/compression stations)
- The entrance and exit to the onshore transport network
- At temporary storage sites along the transport network
- The entrance and exit to the shore facility
- Loading & off-loading locations (e.g., ships)
- At the injection site (e.g., North Sea wellhead)

The following sections describe the measurement related requirements and challenges within the three main stages of the CCUS value chain:

- Capture
- Transportation
- Storage

2.2.1 Capture

The first stage in the CCUS chain is to capture the CO_2 emitted at source to prevent it entering the atmosphere. There are a wide range of technology and policy considerations required at this stage of the process. One such consideration is whether the CO_2 will be captured pre or post combustion or whether oxy-fuel combustion will be deployed [28]. Another consideration is whether only CO_2 is captured or whether multiple components (such as

H_2S, CO, CO_2, NO_2 and SO_2) are captured, processed, and separated into the individual constituents. Viable solutions partly depend on the process but also on the limitations of current technologies [39].

The different process options have diverse flow measurement requirements and challenges. Different capture processes have varying levels of impurities with a typical CO_2 concentration range between 90 % to 99 % [40]. The concentration of CO_2 and percentage of impurities can greatly affect the physical properties and phase behaviour of the resulting mixture [41]. The density may alter significantly as well as the phase envelope, with the possibility of two-phase flow occurring [25].

Pre-combustion Capture

In **pre-combustion**, CO_2 is removed from the fuel ahead of combustion. Here, the process fuel, typically methane or coal that has undergone gasification, is converted into a synthesis gas mixture of hydrogen and carbon monoxide prior to its combustion (Figure 4). The carbon monoxide is then converted to CO_2 via a reaction with water known as the water-gas shift reaction. The H_2 and CO_2 rich gas mixture is then separated into hydrogen and CO_2 to enable a clean combustion process [28]. Accurate flow measurement of medium to high pressure carbon dioxide gas is required in this process. The pressure depends on the type of solvent used to strip the CO_2 from the mixture gas and could be up to 40 bar [40].

The measurement of 40 bar carbon dioxide with minimum impurities should be straightforward. In practice, the absence of traceable primary flow facilities is a significant barrier. The requirement for full traceability of gas CO_2 primary flow facilities will be discussed in Section 2.3. Suitable technology for metering gaseous carbon dioxide includes Coriolis, ultrasonic and differential pressure devices such orifice plate, cone, or venturi. Laboratory trials [42] [20] [43] demonstrate that measuring CO_2 gas at 40 bar with these technologies is possible. However significant further work would be required to evaluate their relative suitability.

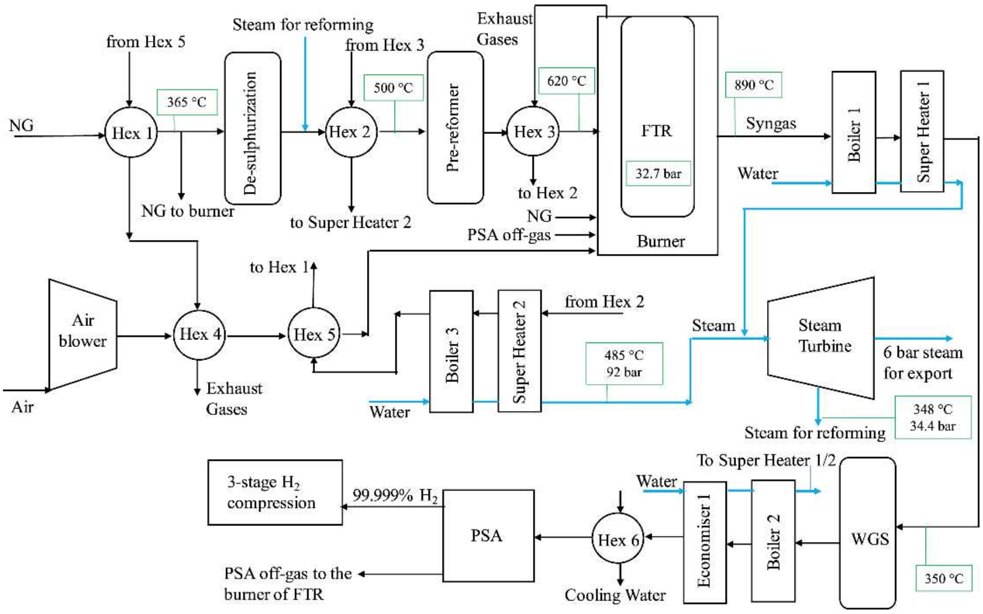

FIGURE 4 PRE-COMBUSTION CARBON CAPTURE PROCESS LAYOUT [44]

Post-combustion Capture

Post-combustion capture of CO_2 is significantly easier to retrofit to existing installations than pre-combustion. This process involves separating the CO_2 from the flue gases produced after combustion of hydrocarbons (Figure 5). Traditional absorption processes use chemical solvents such as amine. However, these are energy intensive and result in the process efficiency dropping by 30 % [28]. New separation methods currently under development use membranes which are potentially much more efficient [45].

The hot flue gas containing CO_2 is cooled to temperatures between 40 °C to 60 °C and then routed to an absorber system. At this stage the CO_2 bonds with the chemical solvent. Afterwards, the CO_2 is removed from the CO_2 rich solvent before being sent to a stripper. The solvent is then regenerated by heating to between 100 °C and 140 °C, and the CO_2 is stripped off [45] [46].

The flow measurement of flue gases containing CO_2 is only required for process control purposes. More accurate flow measurement is required for the CO_2 that has been removed from the flue gas prior to transportation. This is at relatively low pressure and high temperature as most flue gases are at atmospheric pressure [46]. This low pressure can present some challenges, such as attenuation of ultrasound signals, and suggests the requirement for a traceable flow facility for gas at near atmospheric pressures and temperatures around 100 °C to 140 °C [45] [46].

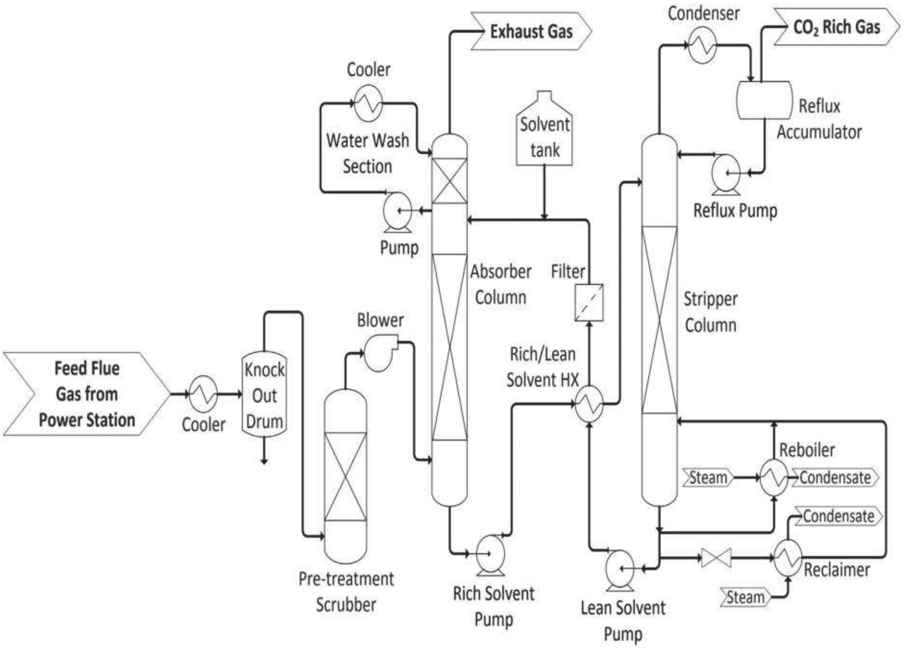

FIGURE 5 POST-COMBUSTION CARBON CAPTURE PROCESS LAYOUT [46]

Oxy-fuel Capture

The final technology for carbon capture considered in this report is **oxy-fuel** capture. Rather than combusting fossil fuels in air, they are burned in pure oxygen. This results in a cleaner combustion with no NO_x gases emitted and only CO_2 and H_2O produced [44]. The flue gas stream contains a far greater concentration of CO_2 than for other combustion processes. The oxy-fuel process is detailed in Figure 6.

Depending on the fuel used and the exact combustion process, between 80 % to 98 % of the flue stream is CO_2 with the remainder being water vapour. This results in a far simpler separation process prior to CO_2 compression and subsequent transportation. The carbon dioxide in this process is captured from the flue gas at relatively low pressures and moderate temperatures [47]. The conditions for the carbon dioxide stream are similar to the post-combustion CO_2 capture process and present similar challenges for flow measurement traceability. The CO_2 is in a gaseous state prior to transportation.

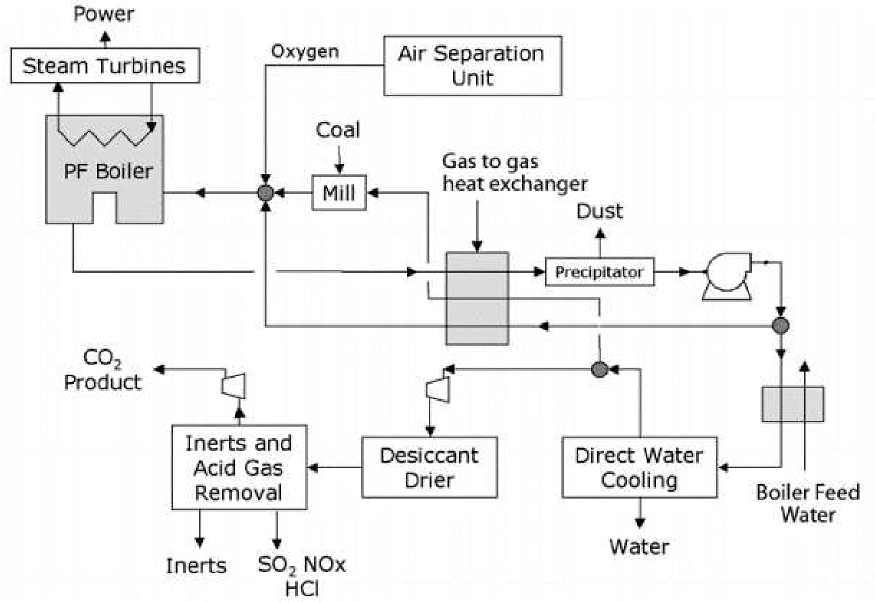

FIGURE 6 OXY-FUEL CARBON CAPTURE PROCESS LAYOUT [40]

At the capture stage, the CO_2 will require regular composition purity checks via gas chromatograph to ensure that the CO_2 entering the transportation network meets the required specification. There will be strict stipulations in place for the quality of the CO_2 stream at the point of entry to the Transportation & Storage (T&S) network. Impurities can substantially alter the phase behaviour of CO_2 and present significant flow measurement challenges (Section 2.1).

Flow measurement at the capture stage will be for gas at 1 - 40 bar and from ambient to over 100 °C [40]. Prior to the compression station the pressure of the gaseous CO_2 will be up to 5 bar for the flue stream. After compression, the CO_2 will be at approximately 30 bar to 35 bar.

Metering of the CO_2 will be required as it exits the capture plant and enters the T&S network. This will enable the capture rate[2] to be determined. If the capture plant is operated by the emitter, then it is likely that there would be no requirement to measure the flow into the capture facility unless the operators want to optimise the process and adhere to good measurement practice. However, if the capture plant is third party operated, then there will be a fiscal measurement requirement to meter and determine the composition of the CO_2 at the outlet from emitter and at the inlet of the capture plant.

The capture rate can be calculated by mass balance between the metering at the inlet of the T&S network and at the outlet of the emitter, or by calculating the material balance between the fuel and feedstock supplied to the emitter and the metering at the inlet of the T&S network.

If there are several parties emitting CO_2 into one capture facility, then there will be a fiscal measurement requirement for metering and compositional analysis of all the individual streams to ensure the correct capture rate is calculated for each.

Figure 7 provides an example of potential measurement nodes along the CCUS capture process. The measurement nodes are purple circles with a white “M” and denote metering and compositional analysis points in the process.

In this scenario, Emitter D operates their own capture plant so there is only a requirement for fiscal metering and compositional analysis at the point of entry into the T&S network. Emitters B & C are separate companies, remotely

---

[2] The proportion of gross CO_2 emissions that are captured

located from, but sharing a common pipeline to, another capture plant. Emitters B & C both require fiscal metering and compositional analysis at their respective outlets and also at the inlet to the capture plant. This enables the captured CO_2 to be apportioned to the appropriate emitter. Emitter A is located near the third party owned capture plant and requires fiscal metering and compositional analysis at the outlet of their plant. Both capture plants require fiscal metering and compositional analysis at their respective inlets to the T&S network.

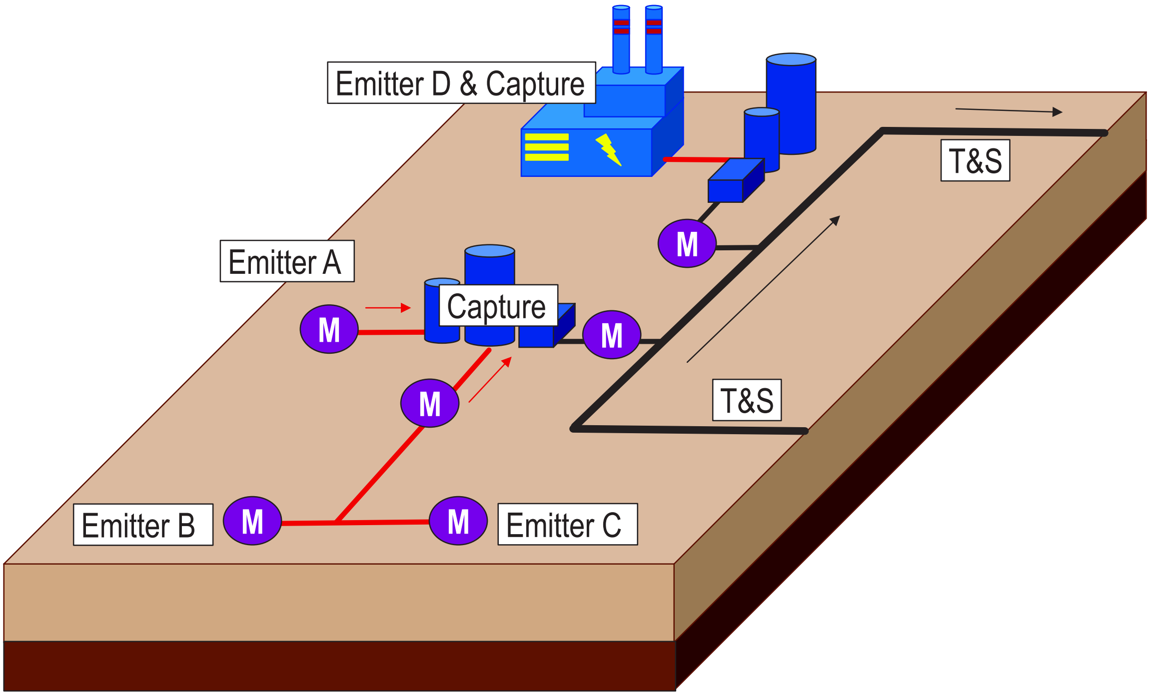

FIGURE 7 CCUS CAPTURE MEASUREMENT NODES

As the **Capture** stage is likely to occur at low to medium pressure, there are several measurement challenges, such as low density and low mass flow rates. Carbon dioxide also presents issues arising from the attenuation of ultrasonic signals. However, there are now ultrasonic flow meters that claim to accurately measure gaseous CO_2 [48] [49]

Other potential technologies include Coriolis and differential pressure meters. The performance, reliability, robustness, and cost of differential pressure devices such as Venturi, cone and orifice plates are well-suited to the measurement of captured CO_2. Coriolis meters have advantages such as direct mass measurement, density measurement and no upstream or downstream installation requirements, but typically have a higher cost than pressure-based instruments. Flow meter technologies for CCUS will be discussed in more detail in Section 2.3.

There is currently no credible traceability chain for gaseous CO_2. No flow calibration facility in the UK or Europe offers gaseous CO_2 as a fluid medium. Flow traceability is a fundamental requirement for the UK's national measurement infrastructure, however currently there are substantial gaps that cannot readily be filled without investment in facilities and research. CO_2 flow traceability will provide the technical proof that a flow measurement device has the appropriate measurement chain referenced back to a UK national measurement standard. **We therefore recommend that the InstMC works with the UK Government and others to explore the options for creating an appropriate traceability chain for CO_2 flow measurement that can replicate the operating conditions employed across the CCUS value chain in the UK.**

2.2.2 Transportation

The transportation mode for CO_2 will depend on the fluid phase, the emission source, its scale, and physical location [50]. It could be transported via pipelines onshore, offshore, or a combination of both [25]. It has been successfully transported in pipelines in the United States of America and Canada since 1972 [51] [52]. In western USA, over 50 $MtCO_2$ is transported by pipeline each year [53]. However, the North American framework is fragmented, with pipelines generally regulated by individual states rather than by a single federal agency [53]. In practice, numerous federal environmental laws, and federal regulations, in coordination with state regulatory agencies, are often involved in the approval of any CO_2 pipeline. Whilst there is support in the US to increase CCUS to combat climate change, projects still encounter a variety of obstacles, and current federal environmental laws and regulations often impede progress [54]. At present the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) has primary authority to regulate interstate CO_2 pipelines under the Hazardous Liquid Pipeline Act of 1979 [55].

It is also expected that CO_2 will be transported by rail, road, or ship [21]. A study [50] found that all of these transportation modes will present different measurement requirements and challenges. As already discussed in Section 1.1, CO_2 is typically in gaseous phase but can also be a supercritical fluid or subcooled liquid depending upon the temperature and pressure conditions [21]. These special characteristics of CO_2 differ from most materials and present several issues and challenges [25].

One of the main difficulties in successfully deploying CCUS will be the provision of a suitable transportation network for CO_2 [28]. The requirements will vary depending upon the stage of the process chain, the fluid phase and the final storage destination. In the short term, and in the absence of pipeline infrastructures, it may be necessary to transport the CO_2 by rail, road, or ship [39]. In the long term, in order to reduce costs, it will be necessary to transport the CO_2 from the point source by pipeline to its final destination [21].

The phase diagram for CO_2 highlights the challenges to its transportation without changing phase (Figure 1). For **liquid** transportation, pipelines must be operated at high pressures of up to 200 bar to maintain CO_2 in the dense liquid phase [50]. Accurately maintaining the pressure and temperature will be critical to ensure a predictable fluid phase condition. When transporting by truck or ship, the CO_2 will require refrigeration between -50 °C to -54 °C with the pressure maintained around 7 bar [53]. This narrow range of conditions is necessary to maintain the CO_2 as a liquid while avoiding solidification.

For economic reasons, when transporting CO_2 over large distances, the preference will be for transporting CO_2 in dense liquid phase. This will facilitate higher flow rates and greater control over pumping operations [25].

When CO_2 is transported via new offshore pipelines, the fluid will likely first be compressed to over 100 bar with temperatures around ambient (~5 °C) [25]. However, existing offshore pipelines are not all capable at operating at such high pressures and instead would operate closer to 30 bar, through to 40 bar [9]. This reduced pressure would imply that unless the CO_2 is sub-cooled and maintained at below - 10 °C, it would have to be transported as gas.

If the CO_2 is to be transported as a **gas**, compression is required to ensure transport efficiency. One advantage of this approach is that the existing gas infrastructure could potentially be used. However, due to the thermodynamic properties of CO_2, the pressure must not rise above the “bubble point” or the phase could change from gas to liquid. This would present significant challenges to the pipeline, pumping, instrumentation, and integrity [25]. The temperature and pressure would therefore need to be maintained below 20 °C and 48 bar respectively [21].

Figure 3 shows the possible transportation measurement nodes both onshore and offshore along the CCUS transportation network. These transportation measurement nodes are denoted as turquoise circles with a white “M” in the diagram.

The transported CO_2 will require regular composition checks via gas chromatograph at various locations along the transportation network. These locations are still to be determined but it is envisioned they will include the following:

- At regular points within the CCUS transport network (e.g., pumping/compression stations)
- The entrance and exit to the onshore transport network
- At temporary storage sites along the transport network
- The entrance and exit to the shore facility
- Loading & off-loading locations (e.g., ships)

When considering flow measurement requirements for CO_2 **Transportation**, currently there is little direct evidence that flow measurement technologies are accurate with dense liquid CO_2 [56] [57]. There are on-going investigations into the performance of conventional flow measurement technologies with Liquefied Natural Gas (LNG) due to the development of a traceable primary standards [57]. However, no such facility exists for liquid CO_2 [21] [20].

For gaseous CO_2, there is limited research into the performance of suitable technologies [42] [21]. There are currently two flow facilities in the world with accreditation with CO_2 as a calibration fluid: FortisBC in British Columbia, Canada has certification for its CO_2 gas flow facility for the calibration of gas turbine flow meters which could be extended to other technologies in the future [20]; and the Exhaust Meter Calibration Facility (EMCF) at the National Institute of Standards and Technology (NIST) in the United States of America. These two facilities do not mitigate the need for two new CO_2 facilities in the UK for dense liquid and gas calibration respectively. Without these two facilities, there will be no direct traceability chain for the flow measurement of CO_2 within the UK. **To address this significant gap, we recommend that InstMC works with the UK Government and others to explore the options create a suitable traceability chain for CO_2 that replicates the conditions experienced within the CCUS value chain**

2.2.3 Storage

The storage of CO_2 is the final and most important stage in the CCUS chain. To ensure that the CO_2 is successfully sequestered, it must be accurately measured at the point of storage. It has been estimated that the UK has approximately 1/3rd of Europe's storage capacity [9]. Whilst there are over one hundred CCUS sites in operation in the world, there is currently only one in the UK – the STEMM-CCS (Strategies for Environmental Monitoring of Marine Carbon Capture and Storage) demonstration project[3] in the central North Sea [58].

The UK sector of the North Sea has sufficient capacity to store around 78 Gt of CO_2 in saline aquifers (Bentham, Mallows, Lowndes, & Green, 2014). Further potential storage exists in the depleted oil & gas wells of the UK North Sea, with a capacity of up to 8 Gt [9]. Whilst disused oil & gas reservoirs have lower capacity, the supporting infrastructure such as well heads and pipelines already exist, and the reservoirs have already undergone intensive geological study. However, these vast potential storage sites will require accurate measurement of flowing CO_2 for optimal reservoir management and safety.

The accurate flow measurement of CO_2 at the wellhead will be used to determine the quantity of CO_2 that has been successfully sequestered. This measurement will be critical for the mass balance approach to calculate the overall CO_2 sequestered rather than emitted to the atmosphere. Accurate and traceable measurement of the quantity of CO_2 captured, transported, and stored, is essential for all stakeholders to be confident in the efficiency and effectiveness of the entire CCUS chain.

For saline aquifers, the pressure will exceed 100 bar, so that the fluid will be in the liquid dense phase [59]. Here, the measurement of CO_2 will be critical for identifying any network losses and must be extremely robust, requiring little or no maintenance. Previous experience from the oil & gas industry suggests that the most suitable technology

---

[3] The purpose of the STEMM-CCS project was to deliver new approaches, methodologies and tools for cost-effective environmental monitoring and leakage quantification at offshore CO_2 storage sites.

for the measurement of liquid dense CO_2 will be differential pressure devices, due to their reliability, repeatability, robustness, measurement uncertainty and their history of operating subsea for oil & gas production.

There is already extensive experience of storing CO_2 in the North Sea [59] [60] [61]. CO_2 has been re-injected into the K12-B gas field located in the Dutch sector of the North Sea since 2004. Approximately 20 kt of CO_2 is injected into the natural gas field per year [61]. This injection of CO_2 is a well-established Enhanced Oil Recovery (EOR) technique. The CO_2 from the natural gas production stream is separated and re-injected to approximately 3800 meters below sea level. This increases the overall pressure of the reservoir and improves the flow of hydrocarbon gases towards the production wells. The temperature, pressure and flow rate of the re-injected CO_2 are all continuously monitored. The injected gas is comprised of approximately 92 % CO_2 with impurities such as CH_4 and other gases. At the wellhead the CO_2 is subcritical due to the lower injection pressure. The flow meter devices used for the measurement of the CO_2 for the injection into the K12-B gas field are differential pressure Venturi meters [61].

In the Yates oil field in Texas, Coriolis flow meters have been used since 1985 to measure the low-pressure CO_2 injected into the reservoir to increase the reservoir pressure and to enhance oil recovery [62]. However, the accuracy of both the differential pressure devices and the Coriolis flow meter is not known due to the lack of traceable flow facilities and independent flow measurement research. In this application the CO_2 was transported to site at supercritical pressure but, due to the losses in the network, the pressure at the wellhead was closer to 55 bar [62]. Accordingly, the fluid phase changed from dense liquid to a two-phase mixture. There is no facility in the world offering traceable flow calibrations of two-phase liquid and gas mixtures. This extremely challenging flow regime would ideally be avoided whenever possible during the design and operation of CCUS storage facilities. If two-phase flow is unavoidable then there would be a requirement for a multiphase flow meter or two-phase wet-gas flow meter. The verification of the performance of these devices with CO_2 as a test fluid medium has not been completed and would require investment in suitable flow facilities.

2.3 Flow Meter Technologies for CCUS

Several different types of flow metering technologies are used in industry to measure the flow of CO_2 for a variety of applications, including CCUS [21]. Numerous techniques can be deployed for the determination of the CO_2 flow rate. They can be separated into two distinct measurement methods:

- Direct metering
- Indirect metering

Direct metering devices include Coriolis and positive displacement meters. These devices directly measure the desired parameter, such as mass or volumetric flow. The more common type of measurement is indirect and occurs when another parameter is measured and then converted ‘indirectly’ to calculate the flow. Examples include ultrasonic, turbine, vortex, differential pressure, thermal mass, and electromagnetic meters.

Another factor to consider is whether they device measures mass or volume. As reporting predominately uses mass based[4] terms, there is a requirement to convert any volumetric flow to mass using accurate fluid properties. This means there will be a requirement for accurate knowledge of the composition and hence density of the CO_2 stream. However, as already discussed in Section 2.1, the phase behaviour of CO_2 in the temperature and pressure ranges of interest for CCUS applications means that this conversion to mass from volume is more complex than for many other fluids.

Fundamentally, the selection of appropriate measurement technology for CCUS applications will come down to availability, compatibility, cost, reliability, and measurement uncertainty. Selecting the most appropriate flow meter

---

[4] The EU ETS measurement uncertainty of ±2.5 % (k=2) is quoted in mass terms.

technology is only one part of the process. Ensuring that it is being used correctly is essential for optimising the measurement process.

It is important to understand that measurement is not an absolute operation, but instead provides an estimate of the ‘true’ value and has an associated uncertainty. The measurement uncertainty (often incorrectly referred to as ’performance accuracy’) is a function of the nominal accuracy of the device (typically determined by the metering technology), the actual operating environment for the instrument, and the instrument calibration. To provide confidence that the measurement data generated by the device is accurate, there needs to be traceability to a higher-level standard, which includes an assessment of the measurement uncertainty. Whilst a device might be of high quality, without a traceable flow calibration, there can be no confidence placed in the quality of the resulting measurement. This is a fundamental issue that will persist for the flow measurement of CO_2 in CCUS applications until a robust traceability chain is created.

Whichever flow meter technology is selected for a CCUS application, certified calibration remains an essential step for ensuring the validity of the entire measurement system. Furthermore, the calibration applies to that meter only, operating under the conditions with which it was calibrated.

Appendix A provides a brief overview on some of the types of flow metering technologies and meters that are potentially suitable for CCUS applications and discusses the potential advantages and disadvantages of each technology with respect to metering CO_2.

2.4 Current Traceability Chain for CCUS

CCUS is the subject of continuous national and international discussion and effort. However, there has yet to be any substantial investment in the core technology and facilities that are needed to underpin the traceability chain for CCUS. At present, there are few traceable flow calibration facilities for carbon dioxide [63]. Whilst there are over 100 flow calibration facilities globally for water and hydrocarbons, there are only two calibration facilities offering carbon dioxide as a test medium [36] [20], and both of these are for gas only [43].

Through the UK’s Clean Growth Strategy, the UK Government wishes to demonstrate international leadership in CCUS and to have the option to deploy it at scale in the UK in the 2030s [64]. Accurate flow measurement requires that flow meters are calibrated through the use of traceable facilities [31].

In the absence of a test and calibration facility for CO_2 (or CO_2 rich mixtures), trials and calibrations may be undertaken using an alternative fluid. For liquid CO_2 the water may be an acceptable substitute and for gaseous CO_2 available options include air, nitrogen, or natural gas. However, without research to verify that these approaches are valid, there remains the concern that these trials and calibrations do not represent realistic CCUS conditions. This ultimately means that there is no valid traceability chain for the flow measurement of carbon dioxide. This goes against metering best practice and OGA guidelines [65].

The way to build confidence in the flow measurement of CO_2 would be to have access to traceable flow facilities that use CO_2 (in its different phases) as a test medium [31]. **We recommend that the InstMC works with the UK Government and others to explore the various options to address the absence of facilities capable of measuring: gaseous phase gas CO_2 flows, liquid/dense phase CO_2 flows and supercritical phase CO_2 flows.**

2.4.1 Gaseous phase

There are currently only two gas flow facilities that calibrate flow meters with carbon dioxide as the test fluid medium. They are the Exhaust Meter Calibration Facility (EMCF) at the National Institute of Standards and Technology (NIST) in the United States of America [66] and FortisBC in British Columbia, Canada. However, FortisBC do not have a primary reference and only has certification for their CO_2 gas flow facility for the calibration of gas turbine flow meters [20]. The flow reference used at FortisBC is a secondary master meter system which comprises of turbine flow meters that have been calibrated in natural gas at the Dutch National Measurement Institute (NMi). As such, FortisBC cannot claim to have a valid traceability chain for the measurement of gas CO_2.

The Exhaust Meter Calibration Facility (EMCF) at the National Institute of Standards and Technology (NIST) is a primary gas standard facility that has several different gases, including CO_2, available as test fluids. The facility uses critical flow nozzles that have been calibrated using one of NIST's gas flow standards. They include piston provers, bell provers and a PVTt system. The flow range varies from 3.6 m^3/h to 372 m^3/h with temperatures ranging from 293 K to 700 K. The facility has an uncertainty of less than 1 % (k=2) [66]. The accredited flow ranges are well below the standard operating conditions encountered in CCUS CO_2 gas flow. This means that there would be no direct traceability chain for the calibration of CO_2 gas flow meters at operating conditions. The only possible traceability chain would rely on "boot-strapping" from a low flowrate primary reference up to a medium and high flow rate via a manifold of multiple flow meters. This could significantly increase the overall measurement uncertainty due to the correlation uncertainty being cumulative rather than the standard root sum squared method. This would have a clear and direct effect on the overall permissible measurement uncertainty of CO_2 gas flow. A schematic of the facility is given in Figure 8.

We therefore recommended that InstMC works with the UK Government and others to consider the options to provide a suitable traceability chain within the UK for gaseous phase carbon dioxide flows.

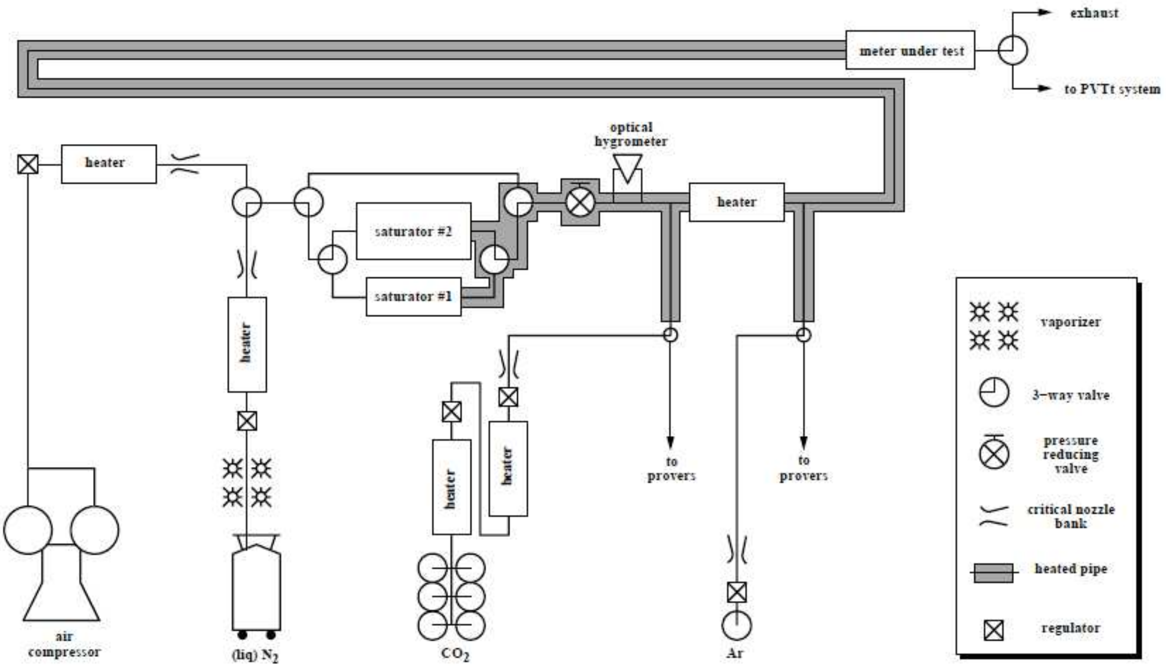

FIGURE 8 SCHEMATIC OF NIST'S EXHAUST METER CALIBRATION FACILITY [66]

2.4.2 Liquid/dense phase

There are no traceable liquid/dense phase carbon dioxide flow calibration facilities in the world. This means that the flow measurement of liquid/dense phase carbon dioxide flow cannot be validated and linked to a primary standard. This ultimately means that there is no method of verifying the measurement of liquid/dense phase carbon dioxide so that significant errors could arise in large scale CCUS schemes. This will have a direct impact on fiscal transactions, health and safety, process monitoring and environmental compliance.

We therefore recommended that InstMC works with the UK Government and others to investigate the options to develop a liquid/dense phase carbon dioxide flow calibration facility to provide a suitable traceability chain within the UK.

2.4.3 Supercritical phase

There are no traceable supercritical phase carbon dioxide flow calibration facilities in the world. This means that the flow measurement of supercritical phase carbon dioxide flow cannot be validated and linked to a primary standard. This ultimately means that there is no means of verifying the measurement of supercritical phase carbon dioxide so that significant errors could arise in large scale CCUS schemes. This will have a direct impact on fiscal transactions, health and safety, process monitoring and environmental compliance.

We therefore recommended that InstMC works with the UK Government and others to investigate the options to provide a suitable traceability chain within the UK for supercritical phase carbon dioxide flows.

2.5 Regulation Landscape

Whilst CCUS has been a topic of debate and discussion for several decades now, the status of CCUS Regulations is in their infancy. This section of the report will review the status of regulations in the UK, the European Union, and the rest of the world.

2.5.1 United Kingdom

There are currently no regulations for CCUS in the UK, although these are likely to emerge as the CCUS value chain evolves. Some Regulations will undoubtedly require a specialist flow measurement component. **We recommend that the UK's Designated Institute for flow measurement is consulted over this element of the coming Regulations**. It is noted that the UK government are currently formulating a framework for CCUS in the UK [67].

2.5.2 European Union

European regulations for CCUS are fairly comprehensive. There are two main regulations – the CCS directive [68] and the EU Emissions Trading System [3]

The CCS directive on the geological storage of CO_2 establishes a legal framework for the environmentally safe geological storage of CO_2 to contribute to the reduction in anthropogenic carbon dioxide emissions [68]. It specifies extensive requirements for selecting potential sites for CO_2 storage. A storage site can only be selected after completing the required analysis where the results demonstrate that, under the proposed conditions of use, there are no significant risks of leakage or damage to human health or the environment. No geological storage of CO_2 can be undertaken in the EU without a storage permit [68].

The EU ETS is the main legislation in the European Union's policy to combat climate change [3]. It is the world's first major carbon market and is still the largest. The Emissions Trading System ensures that in case of leakage the operator has to surrender allowances for the resulting emissions. Liability for local damage to the environment is dealt with by the Directive on Environmental Liability. Liability for damage to health and property is left for regulation at Member State level.

The EU ETS works on the 'cap and trade' principle. A 'cap' is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. This cap is then reduced over time so that total emissions fall within the agreed timescales. Within the cap, installations buy or receive emissions allowances, which they can 'trade' with one another as required. The limit on the total number of allowances available ensures that they have a value linked to them. This is known as the 'carbon price'.

After each year, an installation must surrender enough allowances to fully cover all of its emissions, otherwise heavy fines are imposed. If an installation reduces its emissions, it can keep the spare allowances to cover future needs or else sell them to another installation that is short of allowances.

Trading brings flexibility that ensures emissions are cut where it costs least to do so. A robust carbon price also promotes investment in innovative, low-carbon technologies.

2.5.3 Rest of the World

The International Energy Agency (IEA) has repeatedly highlighted the importance of legal and regulatory frameworks to underpin widespread deployment of carbon capture, utilisation and storage (CCUS). They have stated that as well as "*ensuring the safety and security of CCUS activities, regulatory frameworks are also important to clarify the rights and responsibilities of CCUS stakeholders, including relevant authorities, operators, and the public, and to provide certainty for project investors*". The IEA are releasing a new publication in 2021 that will update the 2010 IEA Model Regulatory Framework [69] and share global best practices for the development of CCUS legal and regulatory frameworks.

In the United States of America, on 25th March 2021, a key CCUS bill was brought before congress to extend the carbon sequestration tax credit through to 2030 [70]. The act is titled the 'Carbon Capture, Utilization, and Storage Tax Credit Amendments Act of 2021' and permits taxpayers to elect to receive a payment in lieu of the tax credits for carbon oxide sequestration and qualifying advanced coal projects.

The bill also makes other modifications to certain carbon sequestration credits, including

- an allowance of carbon sequestration credits against the base erosion minimum tax
- modifications to sequestration requirements for certain qualifying advanced coal project credit equipment
- an increase in the sequestration credit value for direct air capture projects.

According to the IEA, the required guidelines and regulations for the implementation of CCUS in the Southeast Asia region have still to be developed [71]. However, Japan launched the Asia CCUS Network in 2021 to provide a platform for policymakers, financial institutions, industry players, and academia to work together to ensure the successful development and deployment of CCUS in the Asia region [72]. It includes members from Japan, Australia, Cambodia, Indonesia, India, Lao, Malaysia, Myanmar, Philippines, Singapore, Thailand, USA, and Vietnam.

China has set targets to be carbon neutral by 2060 via the 30/60 plan (carbon peaking by 2030). However, the Global CCS Institute have stated that China's lack of a regulatory framework for CCUS is a key barrier for large-scale CCUS deployment [73]. This view has also been stated when reviewing China's 'Five-year Plan' for CCUS policy [74].

2.6 Documentary Standards

Documentary standards (DS) are universally recognised as a vital element of translating research knowledge and technological innovation into effective practical guidance to industry. They drive competitive advantage and sustain economic growth through efficient industrial processes. In order to ensure the world adheres to similar good practice and guidelines for CCUS, a wide range of documentary standards will be required. Furthermore, comprehensive standards and regulations for CO_2 are essential to enable the development and optimal operation of a CCUS chain in the UK as set out in the UK industrial strategy report [75], the Ten Point Plan report [1] and the Powering our Net Zero white paper [5]. This section summarises the status of Documentary Standards for CCUS applications.

At present seven documentary standards relate to CCUS. However, these are not adequate and require significant revision.

ISO/TR 27921:2020 describes the most likely compositions of the CO_2 stream downstream of the capture unit and considers common purification options [76]. It also identifies the potential impacts of impurities on all components of the CCUS chain.

ISO27913:2016 specifies additional requirements and recommendations not covered in existing pipeline standards for the transportation of CO_2 streams from the capture site to the storage facility via pipeline [77].

There are several gaps in these first two ISO standards that must be resolved:

- measurement procedures and flow metering technologies are not specified
- the impact of impurities and phase change behaviour on the performance of flow meters is not discussed
- there is no mention of measurement or calculation methods for fluid properties
- there is no specification for the required threshold levels of carbon dioxide stream impurities
- sampling and measurement methods to determine impurity concentration are poorly defined

Some of these gaps are due to the current lack of technical knowledge. At present there is insufficient technical data to revise the standards due to the lack of CO_2 flow and composition measurement experimental facilities worldwide.

ISO 10790:2015 is a guide for end users on the selection, testing, inspection, operation, and calibration of Coriolis flowmeters [78]. Coriolis meters are recognised as a preferred option to meter CO_2 in liquid and dense phase. However, ISO 10790 does not detail the use and performance of Coriolis meters in CO_2 applications. It is likely that phase change will occur during operation causing a small amount of gaseous CO_2 to be present (bubbly flow) in particular during loading and offloading of CO_2 transportation ships. This will induce an error in the flow measurement, which however can be corrected. ISO 10790 does not detail application and correction methods for Coriolis meters subjected to bubbly flow.

ISO 5167:2003 specifies the geometry, method of use and flowrate calculation equations of differential pressure (DP) devices used to meter gaseous and liquid flows in pipelines [79] [80] [81]. DP devices are a robust choice to meter CO_2 rich mixtures compared to other metering technologies. These DP technologies may be less sensitive to the fluid type and might not need to be calibrated with the process fluid. However, there is no evidence that the calculation equations provided in ISO 5167 for the discharge coefficient and the expansibility factor can be applied to CO_2 rich mixtures so that they can perform within their stated uncertainty.

ISO 9300:2005 specifies the geometry and method of use of Critical Flow Venturi nozzles (CFVN) used to determine the mass flowrate of a gas flowing through a system [82]. Sonic nozzles are widely used as reference secondary standard and constitute a standardised method to measure inert gases and natural gas flows in the field of legal metrology and calibration laboratories. There is high confidence in the use of sonic nozzles as reference devices for the calibration of flow meters for carbon dioxide applications (CCUS). However, the validity of the ISO 9300 for CO_2 rich mixtures is currently unproven.

ISO/TR 11583:2012 and ISO/TR 12748:2015 cover the measurement of flow in wet gas conditions [83] [84]. Wet-gas flow will occur along the CCUS chain depending on temperature and pressure conditions. This may be exacerbated by the presence of impurities in the CO_2 stream. Wet-gas flow is known to have adverse consequences on single-phase flow meter performance. ISO/TR 11583:2012 describes the measurement of wet gas with differential pressure meters and would be applicable to CCUS applications. ISO/TR 12748:2015 describes production flow measurement of wet natural gas streams with different flow technologies in surface and subsea facilities. Neither of these documentary standards mention CCUS applications.

It must be noted that additional documentary standards are likely to be developed as CCUS technologies and applications evolve. These are likely to entail a specialist Metrology component, requiring consultation with the DI.

2.7 Future Needs

The UK Government, working with industry, should ensure that there is a traceable and suitably accurate flow measurement chain for CO_2 within the UK. It will be essential for enabling domestic and international CCUS schemes to be realised – you cannot be confident in a measurement with no traceable reference.

3. SUMMARY

Flow measurement will play a fundamental role in CCUS schemes, whereby all CO_2 is accurately measured through each stage of the CCUS chain. These essential measurements will need to be traceable for the full range of fluid phases and mixtures generated through the CCUS chain.

Within each of the Capture, Transportation and Storage stages, there will be different flow measurement requirements. At present there is very limited CCUS traceability and a lack of technical knowledge and underpinning research. The knowledge gap arises from the limited availability of traceable experimental data for flow measurement of CO_2 in a variety of fluid phases, flow rates, temperature, and pressures. This limitation can only be overcome through investment.

Measurement challenges persist due to the physical properties of CO_2 but also due to the lack of traceable data for flow measurement technologies. Whilst the unique physical properties of CO_2 are unalterable, the lack of traceable data could certainly be resolved through adequate funding and support.

An operational CO_2 flow traceability chain will provide certified verification that a flow measurement device has a validated uncertainty performance referenced back to the national standard. This traceability chain will support the development of key documentary standards and CCUS regulations that are relevant and up to date, as well as promoting new research and innovation.

There are several key recommendations arising from this review of measurement requirements for Carbon Capture, Utilisation and Storage, and they will be presented in the next section.

4. RECOMMENDATIONS

Our key recommendations are as follows:

- The InstMC works with the UK Government and others to explore the options for a suitable traceability chain for CO_2 replicating the conditions experienced during the CCUS value chain in the UK (Section 2.2).
- The InstMC works with the Government and others to investigate the options to provide a suitable traceability chain within the UK for gaseous phase carbon dioxide flows (Sections 2.2.1 and 2.4.1).
- The InstMC works with the Government and others to investigate the options to provide a suitable traceability chain within the UK for liquid/dense phase carbon dioxide flows (Sections 2.2.2 and 2.4.2).
- The InstMC works with the Government and others to investigate the options to provide a suitable traceability chain within the UK for supercritical phase carbon dioxide flows (Section 2.4.3).
- Within forthcoming UK CCUS Regulations any essential specialist flow metrology component should be based on advice from the Designated Institute for Flow Measurement (Section 2.5.1).

END OF REPORT

REFERENCES

[1] UK Government, “The Ten Point Plan for a Green Industrial Revolution,” UK Government, London, 2020.

[2] UK Government, “CCUS Supply Chains: a roadmap to maximise the UK's potential,” UK Government, London, 2021.

[3] European Union, “EU ETS Handbook,” European Union, Brussels, 2015.

[4] House of Commons Library, “The UK Emissions Trading Scheme,” 4 May 2021. [Online]. Available: https://researchbriefings.files.parliament.uk/documents/CBP-9212/CBP-9212.pdf. [Accessed 24 08 2021].

[5] UK Government, “Powering our Net Zero Future,” UK Government, London, 2020.

[6] International Energy Agency, “Net Zero by 2050,” IEA, Paris, 2021.

[7] BP, “BP statistical review of world energy,” BP, London, 2021.

[8] International Energy Agency, “Global CO2 emissions in 2019,” 11 February 2020. [Online]. Available: https://www.iea.org/articles/global-co2-emissions-in-2019.

[9] M. Bentham, T. Mallows, J. Lowndes and A. Green, “CO2 STORage Evaluation Database (CO2 Stored). The UK's online storage atlas,” *Energy Procedia,* pp. 5103-5113, 2014.

[10] United Nations, “Paris Agreement,” United Nations, Paris, 2016.

[11] International Energy Agency, “CCUS in Clean Energy Transitions,” IEA, Paris, 2020.

[12] N. MacDowell, P. Fennel, N. Shah and G. Maitland, “The role of CO2 capture and utilization in mitigating climate change,” *Nature,* 2017.

[13] IPCC, “The Special Report on Global Warming of 1.5 °C,” IPCC, Geneva, 2018.

[14] M. Naranjo, D. Brownlow and A. Garza, “CO2 Capture and Sequestration in the Cement Industry,” *Energy Procedia,* pp. 2716-2723, 2011.

[15] H. Daggash, C. Heuberger and N. MacDowell, “The role and value of negative emissions technologies in decarbonising the UK energy system,” *International journal of Greenhouse Gasa Control,* vol. 81, pp. 181-198, 2019.

[16] UK Government, “UK hydrogen strategy,” UK Government, London, 2021.

[17] R. Soltani, M. Rosen and I. Dincer, “Assessment of CO2 capture options from various points in steam methane reforming for hydrogen production,” *International Journal of Hydrogen Energy,* vol. 39, no. 35, pp. 20266-20275, 2014.

[18] TUV SUD National Engineering Laboratory, “A study of measurement issues for Carbon, Capture and Storage (CCS),” NEL Report 2009_54, Glasgow, 2009.

[19] V. Vilarrasa, O. Silva, J. Carrera and S. Olivella, “Liquid CO2 injection for geological storage in deep saline aquifers,” *International Journal of Greenhouse Gas Control,* vol. 14, pp. 84-96, 2013.

[20] J. Kocbach, M. Holstad, A. Skalvik, K. Folgero, B. Ystad, K. Lohne, E. Soldal, s. Losnegard, A. Paulsen, G. Mouton and L. Teberikler, “Where do we stand on flow metereing for CO2 handling and storage?,” in *38th International North Sea Flow Measurement Workshop*, Aberdeen, 2020.

[21] G. Collie, M. Nazeri, A. Jahanbakhsh, C. Lin and M. Maroto-Valer, “Review of flowmeters for carbon dioxide transport in CCS applications”.

[22] M. Nazeri, M. Maroto-Valer and E. Jukes, “The Fiscal Metering of Transported CO2-Rich Mixtures in CCS Operations,” *Energy Procedia,* vol. 114, pp. 6766-6777, 2017.

[23] N. Glen and L. Hunter, “Measurement Challengs for Carbon Capture and Storage,” *Measurement and Control,* vol. 44, no. 3, 2011.

[24] J. Serpa, J. Morbee and E. Tzimas, “Technical and Economic Characteristics of a CO2 Transmission Pipeline Infrastructure,” European Commission - JRC, Brussels, 2011.

[25] DNV, “Recommended practice - Design and operation of CO2 pipelines,” DNV, 2010.

[26] M. Reader-Harris and E. Graham, “An Improved Model for Venturi-tube Over-reading in Wet Gas,” in *27th International North Sea Flow Measurement Workshop*, Tonsberg, 2009.

[27] C. Mills and R. Belshaw, “Assessing the performance of conventional flow meters in viscous fluids with entrained gas,” in *10th South East Asia Hydrocarbon Flow Measurement Workshop*, Kuala Lumpur, 2011.

[28] A. Osman, M. Hefny, A. Elgarahy and D. Rooney, “Recent advances in carbon capture storage and utilisation technologies: a review,” *Environmental Chemistry Letters,* pp. 797-849, 2021.

[29] R. Porter, M. Fairweather, M. Poukashanian and R. Wooley, “The range and level of impurities in CO2 streams from different carbon capture sources,” *International Journal of Greenhouse Gas Control,* vol. 36, pp. 161-174, 2015.

[30] B. Wetenhall, J. Race and M. Downie, “The Effect of CO2 Purity on the Development of Pipeline Networks for Carbon Capture and Storage Schemes,” *International Journal of Greenhouse Gas Control,* vol. 30, pp. 197-211, 2014.

[31] TUV SUD National Engineering Laboratory, “Feasibility Study for CO2 Test Facilities in Support of CCS,” NEL Report 2010/389, Glasgow, 2010.

[32] S. Pierucci, J. Klemeš, L. Piazza and S. Bakalis, “Effects of Impurities on CO2 Pipeline Performance,” *Chemical Engineering Transactions,* vol. 57, 2017.

[33] S. Martynov, N. Daud, H. Mahgerefteh, S. Brown and R. Porter, “Impact of stream impurities on compressor power requirements for CO2 pipeline transportation,” *International Journal of Greenhouse Gas Control,* vol. 54, pp. 652-661, 2016.

[34] A. Chapoy, M. Nazeri, M. kapateh, R. Burgass, C. Coquelet and B. Tohidi, “Effect of impurities on thermophysical properties and phase behaviour of a CO2-rich system in CCS,” *International Journal of Greenhouse Gas Control,* vol. 19, pp. 92-100, 2013.

[35] K. Harper, J. Lansing and T. Dietz, “Field Experience of Ultrasonic Flow Meter Use in CO2-Rich Applications,” in *27th North Sea Flow Measurement Workshop*, Tonsberg, 2009.

[36] C. Hardie, “Developing Measurement Facilities for Carbon Capture and Storage,” *Measurement and Control,* vol. 46, no. 2, 2013.

[37] E. Kustova, M. Makhonoshina and A. Kosareva, “Relaxation processes in carbon dioxide,” *Physics of Fluids,* vol. 31, 2019.

[38] S. Ghanaatian, E. Joonaki, S. Garcia and M. Maroto-Valer, “From CO2 Transportation in Pipelines to Storage in Geological Formations:The Whole Picture of a Carbon Capture and Storage (CCS) Process with Chemical Thermodynamics,” in *82nd European Association of Geoscientists and Engineers (EAGE) Conference and Exhibition*, Amsterdam, 2020.

[39] T. Wilberforce, A. Olabi, E. Sayed, K. Elsaid and M. Abdelkareem, “Progress in carbon capture technologies,” *Science of the Total Environment,* 2021.

[40] B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer, “IPCC Special Report on Carbon Dioxide Capture and Storage,” IPC, 2005.

[41] A. Murugan, T. Gardiner, R. Brown, P. Brewer, D. Worton, T. Bacquart, R. Robinson and A. Finlayson, “Purity requirements of carbon dioxide for carbon capture and storage,” NPL, 2019.

[42] M. Reader-Harris, D. Addison, J. Barnett and K. Mistry, “Orifice plate pressure loss ratio: theoretical work in compressible flow and experimental work in CO2,” National Grid, 2019.

[43] D. George, H. Fraser, M. Nored and P. Tang, “Carbon Dioxide as a Test Fluid for Calibration of Turbine Meters,” Forties BC Energy, 2020.

[44] S. Nazir, J. Cloete, S. Cloete and S. Amini, “Efficient hydrogen production with CO2 capture using gas switching reforming,” *Energy,* pp. 372-385, 2019.

[45] J. Amann and C. Bouallou, “A new aqueous solvent based on a blend of N-methyldiethanolamine and triethylene tetramine for CO2 recovery in post-combustion: Kinetics study,” *Energy Procedia,* pp. 901-908, 2009.

[46] M. Bui, I. Gunawan, V. Verheyen, Y. Artanto, E. Meuleman and P. Feron, “Dynamic Modeling and Validation of Post-combustion CO2 Capture Plants in Australian Coal-fired Power Stations,” *Energy Procedia,* pp. 2694-2702, 2013.

[47] G. Bagheri, E. Ranzi, M. Pelucchi, A. Parente, A. Frassoldati and T. Faravelli, “Comprehensive kinetic study of combustion technologies for low Comprehensive kinetic study of combustion technologies for low,” *Combustion and Flame,* pp. 142-155, 2020.

[48] K. Harper and T. Dietz, “Field Experience of Ultrasonic Flow Meter Use in CO2-Rich Applications,” in *North Sea Flow Measurement Workshop*, Tonsberg, 2009.

[49] J. Wenzel, “Evaluations on CO2 Rich Natural Gas,” in *European Flow Measurement Workshop*, Noordwijk, 2015.

[50] S. Lovseth, Y. Arellano, H. Deng, F. Finotti, E. Jukes and G. Bottino, “Enabling CCS via Fiscal Metering,” in *Trondheim Conference on CO2 Capture, Transport and Storage*, Trondheim, 2021.

[51] R. Steeneveldt, B. Berger and T. Torp, “CO2 Capture and Storage: Closing the Knowing–Doing Gap,” *Chemical Engineering Research and Design,* pp. 739-763, 2006.

[52] R. Haszeldine, “Carbon Capture and Storage: How Green Can Black Be?,” *Science,* pp. 1674-1652, 2009.

[53] IPCC, “Transport of CO2,” IPCC, Geneva, 2018.

[54] R. Nordhaus and E. Pitlick, “Carbon Dioxide Pipeline Regulation,” *The Energy Law Journal,* vol. 30, no. 1, p. 85, 2009.

[55] US Department of Transportation Pipeline and Hazardous Materials Safety Administration, “Hazardous Liquid Pipeline Safety Act of 1979,” US Department of Transportation, Washington DC, 1979.

[56] L. Wang, Y. Yan, X. Wang, T. Wang, Q. Duan and W. Zhang, “Mass flow measurement of gas-liquid two-phase CO2 in CCS transportation pipelines using Coriolis flowmeters,” *International Journal of Greenhouse Gas Control,* pp. 269-275, 2018.

[57] C. Lin, A. Bhattacharji, G. Spicer and M. Maroto-Valer, “Coriolis Metering Technology for CO2 Transportation for Carbon Capture and Storage,” *Energy Procedia,* vol. 63, pp. 2723-2726, 2014.

[58] A. Flohr, A. Schaap, E. Achterberg, G. Alendal, M. Arundell, C. Berndt, J. Blackford, C. Bottner, S. Borisov, R. Brown, J. Bull, L. Carter, B. Chen, A. Dale, D. de Beer, M. Dean, C. Deusner, M. Dewar and D. Connelly, “Towards improved monitoring of offshore carbon storage: A real-world field experiment detecting a controlled sub-seafloor CO2 release,” *International Jounral of Greenhouse Gas Control,* 2021.

[59] A. Furre, O. Eiken, H. Alnes, J. Vevatne and A. Fredrik, “20 years of monitoring CO2-injection at Sleipner,” *Energy Procedia,* vol. 114, pp. 3916-3926, 2017.

[60] O. Hansen, D. Gilding, B. Nazarian, B. Osdal, P. Ringrose, J. Kristoffersen, O. Eiken and H. Hansen, “Snøhvit: The history of injecting and storing 1 Mt CO2 in the fluvial Tubåen Fm,” *Energy Procedia,* vol. 37, pp. 3565-3573, 2013.

[61] V. Vandeweije, B. de Meer, C. Hofstee, F. Mulders, D. D'Hoore and H. Graven, “Monitoring the CO2 injection site: K12-B,” *Energy Procedia,* vol. 4, pp. 5471-5478, 2011.

[62] T. Green, M. Reese and M. Henry, “Two-Phase Co2 Measurement And Control in the Yates oil field,” *Measurement and Control,* vol. 41, no. 7, 2008.

[63] TUV SUD National Engineering Laboratory, “2018/686 - Review of Primary Standard Options for a Carbon Dioxide Facility,” TUV SUD National Engineering Laboratory, Glasgow, 2018.

[64] BEIS, “The Clean Growth Strategy Leading the way to a low carbon future,” HM Government, London, 2017.

[65] O. &. G. Authority, “Guidance Notes for Petroleum Measurement Issue 9.2,” 2015.

[66] J. D. Wright and P. I. Espina, “Flowmeter calibration facility for heated gas mixtures”.

[67] UK Government, “Carbon Capture, Usage and Storage - An update on the business model for Transport and Storage,” UK Government, London, 2021.

[68] European Union, “Directive 2009/31/EC of the European Parliament and of the council,” European Union, Brussels, 2009.

[69] International Energy Agency, “Carbon Capture and Storage: Model Regulatory Framework,” IEA, Paris, 2010.

[70] *S.986 - Carbon Capture, Utilization, and Storage Tax Credit Amendments Act of 2021,* 117th Congress - 25/03/2021.

[71] International Energy Agency, “Carbon capture, utilisation and storage: the opportunity in Southeast Asia,” IEA, Paris, 2021.

[72] Asia CCUS Network, “Asia CCUS Network,” [Online]. Available: https://www.asiaccusnetwork-eria.org/. [Accessed 30 08 2021].

[73] Global CCS Institute, “Overview of organisations and policies supporting the deployment of large-scale CCS facilities,” Global CCS Institutes, Melbourne, 2020.

[74] K. Jiang, P. Ashworth, S. Zhang, X. Liang, Y. Sun and D. Angus, “China's carbon capture, utilization and storage (CCUS) policy: A critical review,” *Renewable and Sustainable Enerbgy Reviews,* vol. 119, 2020.

[75] UK Government, “Industrial Decarbonisation Strategy,” UK Government, London, 2021.

[76] International Standards Organization, “ISO 27921:2020 Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO2 stream composition,” ISO, Geneva, 2020.

[77] International Standards Organization, “ISO 27913:2016 Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems,” ISO, Geneva, 2016.

[78] International Standards Organisation, “ISO10790 - Measurement of fluid flow in closed conduits -- Guidance to the selection, installation and use of Coriolis flowmeters,” ISO, Geneva, 2015.

[79] International Standards Organization, “ISO 5167:2 - Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 2: Orifice plates,” ISO, Geneva, 2003.

[80] International Standards Organization, “ISO 5167-4: Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 4: Venturi tubes,” ISO, Geneva, 2003.

[81] International Standards Organization, “ISO 5167-5: Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 5: Cone meters,” ISO, Geneva, 2016.

[82] International Standards Organisation, “ISO 9300:2005 Measurement of gas flow by means of critical flow Venturi nozzles,” ISO, Geneva, 2005.

[83] International Standards Organisation, “ISO 11583:2012 Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits,” ISO, Geneva, 2012.

[84] International Standards Organisation, “ISO 12748:2015 Natural Gas — Wet gas flow measurement in natural gas operations,” ISO, Geneva, 2015.

[85] B. Kettner and B. Meter, “Pick The Proper Flow Meter,” *Chemical Processing,* 2016.

[86] M. Mohitpour, A. Jenkins and G. Nahas, “A generalized overview of requirements for the design, construction, and operation of new pipelines for CO2 sequestration,” *The Journal of Pipeline Engineering,* vol. 7, no. 4, pp. 237-251, 2008.

[87] L. Teng, D. Zhang, Y. Li, W. Wang, L. Wang, Q. Hu, X. Ye, J. Bian and W. Teng, “Multiphase mixture model to predict temperature drop in highly choked conditions in CO2 enhanced oil recovery,” *Applied Thermal Engineering,* vol. 108, pp. 670-679, 2016.

[88] S. Mawalkar, A. Burchwell, N. Gupta, M. Place, M. Kelley, S. Winecki, R. Mannes and R. Pardini, “Achieving ~1 Million Metric Ton CO2 Stored; Measurement and Accounting for Net CO2 Injection in a CO2-EOR Complex,” in *14th International Conference on Greenhouse Gas Control Technologies, GHGT-14*, Melbourne, 2018.

[89] NFOGM, “Handbook of Multiphase Flow Metering,” NFOGM, Oslo, 2005.

[90] G. Falcone and C. Alimonti, “The Challenges of Multiphase Flow Metering: Today and Beyond,” in *ASME 2007 26th International Conference on Offshore Mechanics and Arctic Engineering*, San Diego, 2007.

[91] O. Bo, A. Wee and I. Skjaeldal, “Tomography Powered 3-phase Flow Metering in the Wet Gas Regime,” in *South East Asia Hydrocarbon Flow Measurement Workshop*, Kuala Lumpur, 2009.

[92] B. Pinguet, E. Guerra, H. Holmes and W. Angulo, “Outstanding Performance in Heavy Oil application with Vx Technology,” in *South East Asia Hydrocarbon Flow Measurement Workshop*, Kuala Lumpur, 2007.

[93] D. Stewart, D. Hodges, R. Steven and R. Peters, “Wet Gas Metering with V-Cone Meters,” in *North Sea Flow Measurement Workshop*, Peebles, 2002.

[94] C. Mills and R. Belshaw, “Measurement of flow in viscous fluids using a helical blade turbine,” in *North Sea Flow Measurement Workshop*, Tonsberg, 2011.

[95] KTH Mechanics, “Flow Measuring Techniques in Steady and pulsating compressible flows,” KTH Mechanics, Stockholm, 2010.

[96] International Standards Organization, “ISO 2715:2017 Liquid hydrocarbons — Volumetric measurement by turbine flowmeter,” ISO, Geneva, 2017.

[97] International Standards Organisation, “ISO12242 - Measurement of fluid flow in closed conduits — Ultrasonic transit-time meters for liquid,” ISO, Geneva, 2012.

[98] Emerson MicroMotion, “Micro Motion® ELITE® Coriolis Flow and Density Meters,” Emerson MicroMotion, 2016.

[99] Endress & Hauser, “Proline Promass 84X,” [Online]. Available: https://portal.endress.com/wa001/dla/5000492/2813/000/01/TI00111DEN_0214.pdf. [Accessed 14 August 2018].

[100] Krohne, “Optimass 2000 Technical Datasheet,” Krohne, 2010.

[101] C. Lin, M. Nazeri, A. Bhattacharji, G. Spicer and M. Maroto-Valer, “Apparatus and method for calibrating a Coriolis mass flow meter for carbon dioxide at pressure and temperature conditions represented to CCS pipeline operations,” *Applied Energy,* vol. 165, no. 1, pp. 759-764, 2016.

[102] M. Henry, M. Tombs, M. Zamora and F. Zhou, “Coriolis mass flow metering for three-phase flow: A case study,” *Flow Measurement and Instrumentation,* vol. 30, pp. 112-122, 2013.

[103] C. Mills, “Correcting a Coriolis meter for two phase oil & gas flow,” in *South East Asia Hydrocarbon Flow Measurement Workshop*, Kuala Lumpur, 2015.

APPENDIX A – FLOW METER TECHNOLOGIES FOR CCUS

This appendix provides a brief overview of flow metering technologies that are potentially suitable for CCUS applications and highlights the potential advantages and disadvantages of each technology with respect to metering CO_2.

A.1 Differential Pressure (DP) Meters

The majority of flow meters used in the world today are based on differential pressure devices [83]. Differential pressure flow meters are used for both single phase liquid, single phase gas and even multiphase phase liquid and gas flow. Their performance in a variety of fluids is well understood and documented [78] [77] [79] and they have the benefit of being relatively robust and extremely repeatable. They require little maintenance and have a low risk of damage due to the absence of moving parts. These devices have a long track record of measuring CO_2 and are used widely in Enhanced Oil Recovery (EOR) applications.

There are several types of differential pressure devices but the most common are the orifice plate, Venturi and cone meter. Each is described in the following sections.

A.1.1 Orifice Plate Meters

Decades of experience exists for orifice plates measuring CO_2 for EOR projects [84] [85] [86]. They are particularly useful for gas measurement but have also been used successfully for liquid flow applications. If the fluid properties are accurately known, then orifice plates may provide low flow measurement uncertainty. One of the main benefits of orifice plates is that certain model types and nominal diameters can be used without a flow calibration with a known uncertainty of 1 % (k=2). The discharge coefficient for the device can be taken from International Standard ISO 5167:2 [79]. However, the exact composition of CO_2 and the resulting density must be accurately known.

For steady-state, single phase CO_2 flow streams orifice plates may have reported measurement uncertainties within ± 1 % (k=2) [42]. This performance is claimed for both single-phase liquid CO_2 and single-phase gas CO_2. However, this has not been verified at a traceable flow laboratory using CO_2 as the calibration medium. For flow measurement of supercritical CO_2, the performance is unknown at present. However, if the composition, density, and viscosity are known, it is believed that orifice plates might be suitable with no immediately identifiable issues other than a lack of traceable flow data. Accordingly, orifice plates are considered to be well suited to CCUS applications when used with the specified conditions and tolerances.

One potential concern is pressure drop induced phase change. As orifice plates are intrusive to the flow and may create a sizeable pressure loss, consideration must be given to the installation location in the CCUS pipeline to avoid any pressure drop induced phase changes. This is of special concern at operating points where the CO_2 density may change significantly with small variations in pressure and temperature. The risk of phase change at the orifice plate due to pressure drop is unlikely to be significant in a well-designed and managed system.

Another potential concern is that orifice plates require large upstream and downstream straight pipe lengths and / or a flow conditioner installed to ensure a suitable flow profile at the device. It is well documented that a poorly conditioned flow profile may result in measurement errors. It is not uncommon for office plates to require 10 diameters (D) of straight pipework upstream of a flow conditioner, 5 D of straight pipework upstream of the orifice plate and then 5 D of straight pipework downstream of the device.

As with all differential pressure devices, one of the main disadvantages is that they have a small turndown ratio[5] with orifice plates typically operating over a 4:1 ratio. However, by stacking multiple pressure transmitters with differing pressure ranges, differential pressure meters can operate with substantially higher turndown ranges.

A.1.2 Venturi Meters

Venturi meters have the potential to be used for the flow measurement of both single-phase liquid and single-phase gas CO_2 [21]. However, there is currently a lack of experience of using with these devices with CO_2. Whilst sharing the same operation principle as orifice plates, Venturi meters have a lower pressure drop and are more robust but have a slightly higher measurement uncertainty. They are also available over a wide range of pipe diameter sizes.

They share many of the drawbacks of orifice plates such as requiring accurate fluid properties, pressure loss considerations and also installation requirements. There is some knowledge of their behaviour in supercritical fluids but not with supercritical CO_2.

Most commercially available multiphase flow meters incorporate a differential pressure device, typically a Venturi, within their flow meter for the bulk (oil, water and gas) flow rate measurements [87] [88] [89] [90]. As such, they may be suitable for certain two phase CCUS applications.

A.1.3 Cone Meters

The cone meter is a comparable device to the Venturi meter and is commonly used for measuring gas flow [91]. However, to date it has not been used in CCUS / EOR applications or for CO_2 measurement in general. Compared to orifice plates, cone meters have a lower pressure drop, but higher measurement uncertainty. Analogous to Venturis, they have the potential to achieve measurement uncertainty to within 1 % (k=2) for single phase liquid or gas [79]. However, similar to Venturi devices, in order to achieve this uncertainty, individual calibration of the meter in CO_2 would be necessary.

Cone meters have the same advantages and disadvantages as other differential pressure devices. Whilst also available for use in two phase flow conditions, there is very little data available on the uncertainties achievable when operating under such conditions.

A.2 Turbine Meters

Turbine flow meters are still one of the most commonly used flow meters for low uncertainty measurement of high value liquids and gases [92]. They are volumetric devices have been used for decades within industry as a method for measuring both liquid and supercritical CO_2 flow in pipelines [22]. They have been used for CCUS EOR applications with reported uncertainties below 1 % (k=2) [21]. As they are volumetric devices, they require accurate fluid properties of the CO_2 rich stream composition to convert to mass flow.

These are extremely linear, repeatable, and reproducible devices, but, having moving parts, they require regular maintenance and are not suitable for two phase flow [92]. If a turbine meter encounters a phase for which it is not designed, e.g., gas rather than liquid, there is a large risk of mechanical failure.

Turbine flow meters are also extremely sensitive to pulsations and unsteady flow [93]. Due to fluid property effects, it is essential that they are calibrated for the fluid viscosity and operating conditions under which they will be used.

---

[5] Turndown ratio is the maximum flow rate divided by the minimum flow rate.

Although turbine meters can be manufactured for almost any given diameter of pipe, a larger size naturally increases the associated costs of the meter and auxiliary flow conditioning equipment.

Turbine meters also have fairly stringent installation requirements. They typically require 10 D of straight pipework upstream of a flow conditioner, 5 D of straight pipework upstream of the turbine and then 5 D of straight pipework downstream of the device. The turndown ratio for optimum performance is around 6:1 for a turbine meter but they can be used with larger measurement uncertainties with a turndown ratio closer to 10:1 [94]

A.3 Ultrasonic Meters

Whilst there are other types of ultrasonic flow meters such as cross-correlation and Doppler, the most accurate and commonly used is based on transit-time technology. Transit-time ultrasonic flow meters come in a variety of path configurations and are used extensively for fiscal and custody transfer applications in both single-phase liquid and single-phase gas. They are volumetric devices and would require accurate fluid properties of the CO_2 rich stream composition to convert to mass flow.

Historically, ultrasonic flow meters have not been used for CO_2 gas applications due to ultrasound signal attenuation [36]. CO_2 effectively absorbs the ultrasound, making signal resolution extremely difficult at the receiving transducer. In CO_2 the attenuation of an ultrasound signal is due to the relaxation process occurring [37]. The relaxation process is due to the exchange of energy between molecular vibrations and translations and causes the ultrasonic meter to lose signal. The lower the operating pressure, the more significant the problem becomes. Highly sophisticated signal processing is required to resolve a reasonably accurate measurement. Whilst this is not anticipated to be as big a challenge for liquid measurement, insufficient CO_2 applications have been reported to draw firm conclusions.

When operating in the supercritical region where the density may be variable, the transducer frequency required to maximise the signal may extend beyond the range available. Transducers and frequencies are chosen to match the normal range required for common liquids, but the adsorption characteristics of supercritical CO_2 are not well known, especially in large diameter pipes. Furthermore, to obtain an accurate volumetric flow rate from what is a velocity measurement requires corrections for the flow profile which are density and viscosity dependant.

Despite these difficulties, recent developments in transit-time ultrasonic flow meters have shown substantial potential for providing a high accuracy measurement system for CCUS but extensive development, calibration are still required. A number of recent trials in CO_2 rich applications have demonstrated accurate results using an orifice plate as a reference [42]. The use of ultrasonic meter diagnostics could potentially provide additional useful information on density and possibly impurities/concentration. However, these possibilities all require further research and development at a suitable flow calibration facility.

As velocity measurement devices, ultrasonic meters are extremely sensitive to installation conditions and accordingly have rigorous installation requirements. Ultrasonic meters require 10 D of straight pipework upstream of a flow conditioner, 5 D of straight pipework upstream of the meter, and 5 D of straight pipework downstream of the device.

Ultrasonic flow meters are available up to approximately 1220 mm (48 inch) nominal bore for liquid and gas with a minimum size typically of about 100 mm (4 inch). The turndown ratio for optimum performance is around 10:1 but they can be used with significantly larger measurement uncertainties with a turndown ratio closer to 100:1 [95].

A.4 Coriolis Meters

Coriolis flow meters can be utilised for nearly all types of flow applications and have a growing market share in many different industries such as oil & gas, food & beverage, chemicals, and pharmaceuticals. One of the key advantages of Coriolis flow meters is that they provide a direct measurement of the mass flow rate and density with uncertainties as low as 0.05 % for mass and 0.2 kg/m^3 for density [96] [97] [98].

Applied to CO_2 measurement, Coriolis meters have been used extensively at Yates Field in West Texas and at a CCUS plant in North America [54] [60]. Small scale gravimetric trials have also been completed at Herriot-Watt University with pure CO_2 liquid and measurement uncertainties of around 0.11 % (k=2) for mass have been reported [99]. They have also been operated successfully in dense phase / supercritical ethylene applications for custody transfer [55].

Unlike most other flow meter types, a Coriolis meter will not be damaged by changes in fluid phase (although solids could present erosion issues) and hence should be able to operate across the full range of phase conditions that may occur in CCUS applications. There has been significant work by some Coriolis manufacturers in two and three-phase flow [102]. Whilst this isn't applicable to all manufacturers at present, recent developments suggest that most Coriolis meters will in future be able to successfully operate and measure in two-phase conditions, although the measurement uncertainty would be a magnitude higher than single-phase liquid or single-phase gas [100].

Most Coriolis manufacturers claim that their Coriolis flow meters are not adversely affected by installation effects [98] [99] [100]. As such, they should not require long lengths of straight pipe work upstream and/or downstream of the device. Although not overly affected by flow profile disturbances, Coriolis meters should not be installed close to valves that will regularly open and close as this can cause pulsations and vibrations in the flow. This may result in significant errors in the mass flow rate.

The main drawback of Coriolis flow meters is that they are currently limited to around 400 mm diameter. To measure large transportation flow rates, a CCUS metering station would therefore require a manifold comprising of several Coriolis flow meters to meet the flow rate requirements. The turndown ratio for optimum performance is around 10:1 for a Coriolis meter but they can be used with significantly larger measurement uncertainties with a turndown ratio closer to 100:1 [76]

A.5 Vortex Meters

Vortex meters are relatively inexpensive volumetric devices that are often used for process control purposes. They have potential for use with CO_2 gas flow, but their performance is currently unknown due to a lack of published data. Due to their relatively high uncertainty, they would not be suitable for fiscal measurement of CO_2 but could provide a relatively inexpensive method of monitoring CO_2 at the process control level. They have relatively large turndown ratios of approximately 20:1 and little installation requirements (5 D upstream and 3D downstream).

A.6 Thermal Mass Meters

Thermal mass meters are another relatively inexpensive technology that could be used for process control and monitoring of CO_2. However, they require the heat capacity of the mixture CO_2 to be known. This is extremely unlikely for all but pure CO_2. At present, there's very little information on the performance of thermal mass meters for CCUS applications.

INFORMATION

This report is issued as part of the contract under which the work has been carried out for the client by TUV SUD Limited trading as TÜV SÜD National Engineering Laboratory.

NOTES

1. This report may be published in full by the client unless it includes information supplied in confidence by TÜV SÜD National Engineering Laboratory or any third party. Such information, if included within the report, shall be identified as confidential by TÜV SÜD National Engineering Laboratory.
2. The prior written consent of TÜV SÜD National Engineering Laboratory shall be obtained by the client before publication by them of any extract from, or abridgement of, this report.
3. The prior written consent of TÜV SÜD National Engineering Laboratory shall be obtained by the client before publication:
    a. Where such publication is made in connection with any public enquiry, legal proceedings or arbitration.
    b. Where such publication is made in connection with any company prospectus or similar document.
    c. Where the client has notice that TÜV SÜD National Engineering Laboratory is seeking or intends to seek patent or like protection for any intellectual property produced in the course of rendering the services.
4. TÜV SÜD National Engineering Laboratory services are provided subject to terms and conditions acknowledged by our commercial staff and the applicable scope stated in the ISO 9001 certification and/or ISO/IEC 17025 accreditation. Services which fall outside the applicable scope of ISO certification and/or accreditation will be stated in this report.

Revision History

Revision	Date	Description	Author(s)	Approved By
1	07/09/2021	Revised after PS review	Dr Chris Mills	Peter Stojic
2	09/09/2021	Revised after GC review	Dr Chris Mills	Dr Gabriele Chinello
3	24/09/2021	Revised after MH & PS review	Dr Chris Mills	Peter Stojic

Report Production

Contributor(s)	Printed Name	Signature	Date
Author(s)	Dr Chris Mills	Chris Mills	30/09/2021
Reviewer(s)	Dr Gabriele Chinello, Pete Stojic		30/09/2021
Authorised by	Dr Martin Hanton	MDH	30/09/2021

This page is intentionally left blank.