Flow Measurement in Support of Carbon Capture, Utilisation and Storage

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Abstract

Carbon Capture, Utilisation and Storage (CCUS) is a key United Kingdom Government strategy for reducing carbon dioxide (CO_2) emissions to combat the potentially catastrophic effects of climate change. The UK aims to capture and store 10 million tonnes of CO_2 each year by 2030.

Across the entire CCUS value chain, each of the stages require accurate measurement of CO_2 at temperatures, pressures, flow rates and fluid phases that must be validated through a credible traceability chain for flow. This traceability chain would provide the underpinning confidence in meter performance, financial and fiscal transactions and, critically, environmental compliance. The UK-adopted version of the EU Emissions Trading System (EU ETS) has specified an uncertainty value for CO_2 flow measurement that must be adhered to. Accordingly, the provision of accurate and traceable flow measurement of CO_2 in the UK and internationally will be essential for the successful operation of CCUS.

Unfortunately, there are currently no CO_2 flow measurement facilities in the world that are capable of traceable flow calibrations of gas phase, liquid/dense phase and supercritical phase CO_2 that replicate real-world CCUS conditions. The absence of traceable CO_2 gas and liquid flow measurement facilities and accompanying national or international flow measurement standards could seriously impede the widespread deployment of CCUS. These significant barriers could potentially jeopardise the successful implementation of CCUS projects worldwide, not least because these will be governed by legislation and environmental regulations requiring traceable measurement.

This paper presents an overview of the current traceability chain for CO_2 flow measurement in the UK and globally. Current challenges will be detailed along with potential solutions and opportunities for the measurement community.

1. Introduction

In 2021, fossil fuels provided over 75% of global energy by source [1]. According to the International Energy Agency (IEA), in the same year, world energy-related CO_2 emissions were approximately 36.3 gigatons (Gt) [2]. These record-breaking emissions were partly driven by an increase in coal usage. It appears that the economic *recovery* from Covid-19 has not been an environmentally sustainable one.

Carbon Capture, Utilisation and Storage (CCUS) is seen as being crucial in reducing anthropogenic carbon dioxide emissions as part of a transition towards sustainable and clean green energy sources [3] [4]. After decades of little progress, there now appears to be sufficient interest and investment in CCUS schemes globally.

In the UK, CCUS is a key policy within the UK Government's 'Energy White Paper: Powering our net zero future' [5]. As part of the UK's industrial decarbonisation strategy, the UK government has committed to deploy two CCUS clusters by mid-2020s and a further two by 2030 [6]. The two projects announced as the successful track-1 cluster sites were the East Coast Cluster (Teesside & Humberside linked to the Northern Endurance Partnership offshore storage site), and HyNet (Merseyside region and North Wales linked to storage sites in the Irish Sea).

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 [7]. Based on the UK's 2019 CO_2 emissions, this corresponds to approximately 200 years of capacity. Reaching net-zero emissions will be virtually impossible without CCUS [8]. It will be essential in reducing anthropogenic CO_2 emission and will help Paris agreement signatories meet their legally binding greenhouse gas reduction targets [9].

Eradicating all anthropogenic carbon dioxide (CO_2) emissions at source 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 [10]. CCUS is currently 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 [11].

CCUS will also be crucial in providing negative emissions directly through Direct-Air-Capture (DAC) and indirectly through deploying Bioenergy with Carbon Capture & Storage (BECCS) [12]. 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 and manufacturing). Many nations are now aiming to support "*a thriving low carbon hydrogen sector*" [13]. CCUS will be central in supporting the rapid upscaling of low-carbon hydrogen production via steam methane reforming [14]. Methane reforming with CCUS provides a clear pathway for the low-cost generation of hydrogen and will be fundamental in hydrogen strategies.

One often overlooked component in CCUS schemes is the flow measurement of CO_2 [15]. Understanding, monitoring, and controlling the flow rate of CO_2 will be essential for the viable operation of CCUS globally. 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. Unfortunately, there are no accredited flow calibration facilities in the world, that uses CO_2 as the fluid medium, that can fully replicate CCUS conditions. This paper presents an overview of the flow measurement challenges of CO_2, the flow measurement methods, potential technologies for CCUS, along with the regulation landscape.

2. Fluid 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). Whilst not an issue at those conditions, CO_2 readily liquifies at around 57 bar and 20 °C. More challenging, is that at 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 in many regions of the world, 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. The phase diagram for CO_2 and the anticipated CCUS operating range in the CCUS chain are shown in Figure 1.

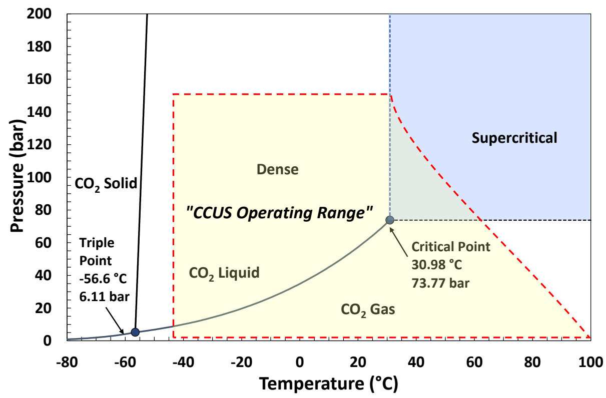

Figure 1: Pure CO_2 phase diagram ("CCUS operating range" highlighted in yellow)

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 [16] [17] [18]. Furthermore, as the phase boundaries lie close together, maintaining the desired fluid phase can be challenging [19] [20] [21]. This is particularly the case for CO_2 transportation across large pipe networks. Regulating the temperature and pressure over pipelines that span hundreds of miles is difficult, when varying climates and elevation can alter the ambient temperature and pressure.

The possibility of phase change is further exacerbated by the likelihood of impurities present in the CO_2 stream. Depending on their type and concentration, impurities may cause significant shifts in phase boundaries, the critical point, and specifically the two-phase region. Impurities could 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 and critical point location, for a mixture of CO_2 and hydrogen (H_2) with varying hydrogen concentration.

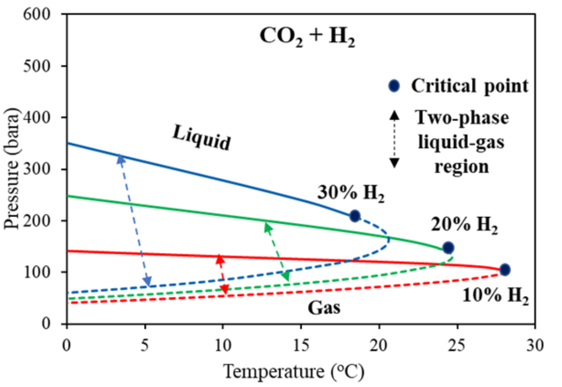

Figure 2: Phase diagram of CO_2/H_2 mixture with varying H_2 concentration

The significant changes in the fluid phase presents flow measurement challenges [17]. It is possible that gas meters might be required at certain points in the network and at other locations liquid meters will be required.

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 [22]. The change in physical properties 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, to ensure the correct operating conditions are maintained [23]. Accordingly, the pure CO_2 phase diagram and equations of state cannot be relied upon for industrial CCUS streams. Physical property software modelling packages could potentially be used to generate fluid property data for the diverse 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 [24] [25]. Whilst this phenomenon is more significant in gaseous CO_2, it has also proved problematic in liquid CO_2 [26]. CO_2 exhibits acoustic attenuation due to a molecular relaxation process [27], 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 the 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 impede flow assurance and pipeline integrity [21]. 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.

3. Measurement stages for CCUS

The measurement locations for CCUS schemes 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., flue gas from 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)

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.

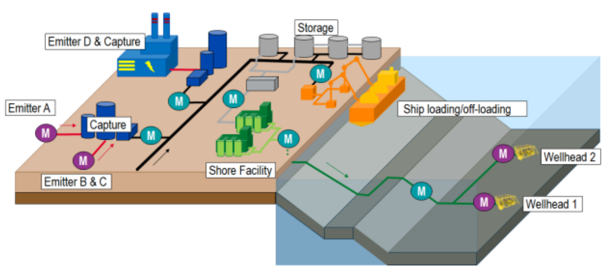

Figure 3: CCUS transportation measurement nodes

To calculate the overall fugitive losses across a CCUS process, a mass balance approach could be used to. This mass balance methodology may also be used to identify any losses across the network up to, and including, the injection wellhead. There will also be a requirement to determine the composition of CO_2 at multiple locations within the CCUS transportation network. This “by difference” method requires low measurement uncertainty flow meters unless the losses are extremely high. However, the most suitable flow meters for CO_2 have not yet been defined.

4. Flow Meters for CCUS applications

CCUS has been the subject of continuous national and international discussion and effort for decades. Unfortunately, there has not been any substantial investment in the core technology and facilities that are needed to underpin the measurement traceability chain for CCUS. 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 [26] [16], and both of these are limited to gas phase [28].

Without sufficient research to verify the performance of flow meters in CO_2, there remains the concern that flow meters might not meet the required uncertainty in all CCUS conditions. This ultimately means that there is a substantial gap in the traceability chain for the flow measurement of carbon dioxide. This goes against metering best practice and regulatory guidelines [29]. In order to build confidence in the flow measurement of CO_2, there needs to be readily available traceable flow facilities that use CO_2 (in multiple different phases) as a test medium [30].

In terms of flow meters for CCUS applications, differential pressure meters show promise for measuring CO_2. There is a history of measuring CO_2 with orifice meters for EOR projects [31] [32] [33]. They are widely used for gas flow applications but are also used extensively for liquid flow measurements. If the fluid properties are accurately known, then orifice meters may provide low flow measurement uncertainty. For steady-state, single phase CO_2 flow streams orifice meters may have reported measurement uncertainties within ± 1 % (k=2) [34]. 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 meters might be suitable with no immediately identifiable issues other than a lack of traceable flow data.

One potential concern is pressure drop induced phase change. As orifice meters 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 temperature and pressure. The risk of phase change at the orifice meter due to pressure drop is unlikely to be significant in a well-designed and managed system.

Turbine flow meters are still one of the most commonly used flow meters for low uncertainty measurement of high value liquids and gases [35]. They have been used extensively as a method for measuring both liquid and supercritical CO_2 flow in pipelines [18]. They have been used for CCUS EOR applications with stated measurement uncertainties of less than 1 % (k=2) [17]. As they are volumetric devices, they 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 [26]. CO_2 effectively absorbs the ultrasound, which makes measuring the signal resolution at the receiving transducer extremely difficult. In CO_2, the attenuation of an ultrasound signal is due to the relaxation process occurring [27]. 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 substantial the issue. Whilst not expected to be as big a challenge for liquid measurement, there is insufficient CO_2 data to provide any worthwhile conclusions at present.

As the density can vary significantly in supercritical CO_2, the ultrasonic transducer frequency required to maximise the signal might extend beyond the frequency offered by the USM. Transducers and frequencies are chosen to match the normal range required for regular fluids, but the adsorption characteristics of supercritical CO_2 mixtures are unknown. This is particularly true for large diameter pipes. Furthermore, as USMs are ultimately velocity measurement devices, the flow profile is extremely important and requires adequate corrections which are dependent on the density and viscosity of the fluid.

Despite these difficulties, recent developments in transit-time ultrasonic flow meters have shown substantial potential for providing a low measurement uncertainty system for CCUS but extensive research and calibrations are still required. A number of recent trials in CO_2 rich applications have confirmed excellent results using an orifice meter as a reference [34].

Coriolis flow meters can be utilised for nearly all types of flow applications and show significant potential for using in CO_2 processes. 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 [36] [37]. 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 [38]. They have also been operated successfully in dense phase / supercritical ethylene applications for custody transfer [39].

Unlike most other flow meter types, a Coriolis meter will not be damaged by changes in fluid phase 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 [40]. 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 [41]. 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 technology is only one part of the process. Ensuring that it is being used correctly is essential for optimising the measurement process.

5. Discussion

"When you can measure what you are speaking about, and express it in numbers, you know something about it." (Lord Kelvin, 1883) [42]

Whilst there is currently funding for CCUS schemes and significant drivers for measuring CO_2, without government support, the requisite traceability chain and regulations will not materialise. Investment and support are required from the top down to ensure that the underpinning science for flow measurement of CO_2 is delivered.

One of the main drivers for improved traceability, R&D investment, and reduced measurement uncertainty, are regulations and International Standards. Whilst CCUS has been a topic of debate and discussion for several decades now, the status of CCUS regulations are limited and vary around the world.

European regulations for CCUS are fairly comprehensive. There are two main regulations – the CCS directive [43] and the EU Emissions Trading System (ETS) [44]. The CCS directive concerns CO_2 geological storage and creates a legal framework for the safe and environmentally sound sequestration of CO_2 to enable the reduction in anthropogenic carbon dioxide emissions [43]. It specifies wide-ranging stipulations for identifying potential CO_2 storage locations. A storage site can only be designated after completing the required analysis where the results demonstrate that, under the planned conditions, there are no significant risks of leakage or potential for environmental disaster. No geological storage of CO_2 can be undertaken in the EU without a storage permit [43].

The EU ETS is the main legislation in the European Union's strategy for the eradicating climate change [44]. It is the first major carbon market in the world and remains the largest. The Emissions Trading System certifies that when a leakage occurs, the operator must surrender allowances for the resulting emissions. The Directive on Environmental Liability oversees the legal responsibility for damage to the environment. Individual liability for damage to health and property is left for regulation at the Member State level.

As of 2022, CCUS schemes in the UK are covered by The Energy Act 2008 [45]. This Act provides for a licensing regime that governs the offshore storage of carbon dioxide. The Carbon Dioxide Regulations 2010 (SI 2010/2221), which transpose many other requirements of the directive, became legislation in October 2010 [46].

The UK government are currently formulating a framework for CCUS in the UK and are due to publish further details in 2022 [47]. In 2022, following BREXIT, the UK have released the UK ETS scheme which is similar to the EU ETS [48].

The International Energy Agency (IEA) has repeatedly specified the requirement for clear legal and regulatory frameworks to underpin the successful implementation 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 updating the 2010 IEA Model Regulatory Framework [49] with a new publication in 2021. This document will disseminate 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 [50]. The act is titled the ‘Carbon Capture, Utilization, and Storage Tax Credit Amendments Act of 2021’ and enables taxpayers to elect to receive a payment in lieu of the tax credits for carbon dioxide sequestration and qualifying advanced coal projects [50].

According to the IEA the required guidelines and regulations for the implementation of CCUS in the Southeast Asia region have still to be developed [51]. 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”* [52]. 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 emissions 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”* [53]. This view has also been stated when reviewing China’s ‘Five-year Plan’ for CCUS policy [54].

It is clear that the approach each region has for CCUS measurement is in different stages of readiness. Flow measurement will play a fundamental role in CCUS schemes around the world. Developing comprehensive regulations, standards, and a detailed traceability chain, will be pivotal in ensuring the successful deployment of CCUS systems worldwide. If one region can demonstrate sufficient accuracy, traceability, and regulations, it will provide a clear framework for others to follow and advance.

6. Conclusion

At present there is very limited traceability, a lack of technical knowledge, and underpinning research in CCUS flow measurement. 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.

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.

The opportunity now exists for the measurement community to develop new traceable CO_2 flow facilities capable of recreating the challenging conditions that CCUS schemes will present. These new facilities will enable cutting-edge research to be completed for the benefit of our environment.

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