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Review of Flowmeters for Carbon Dioxide Transport in CCS Applications

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Abstract

Carbon dioxide (CO₂) emissions from power stations and industrial plants are seen as major contributors to what is known as the greenhouse gas (GHG) effect. Carbon dioxide Capture and Storage (CCS) is one technology which may reduce the quantity of CO₂ released into the atmosphere however, development of CCS has been slowed due to the absence of a viable financial model. Metering technology is a prerequisite in enabling realistic financial decisions to be taken; however, there is currently a paucity of research into the types of flowmeters which would be suitable for incorporating into CCS transportation chains. This paper reviews and summarizes existing metering technologies with a view to establishing their suitability for measuring high mass flowrate, supercritical CO₂. Open channel, differential pressure, velocity measurement, direct mass measurement and electrical, magnetic, thermal, sonic and radiation technologies are all considered. The challenges associated with each generic group are described, and recommendations made regarding the practicalities of using particular types of meter for CO₂ transport in CCS applications.

Key words: CCS, carbon dioxide, CO₂ transport, metering, CO₂ pipeline, flow measurement

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1. Introduction

Climate change, as manifested in global temperature rises, has been a major environmental concern for at least the last two decades [1]. Researchers have concluded that increased quantities of greenhouse gases, especially carbon dioxide CO₂, play a major role in climate change. Increased ocean acidification is also linked to rises in atmospheric CO₂ [1][2]. It is known that the large amount of CO₂ emissions resulting from the utilisation of low price fossil fuel is a significant contributor to the total amount of emitted CO₂ [3][4]. According to an IPCC report from 2000 [5], 90% of anthropogenic emitted CO₂ came from large point sources [6]. A later IPCC report (2014) noted that 49 Gt of CO_{2e} GHG are released worldwide annually [7], with 25% being attributed to electricity and heat production [7]. It has been suggested that one way to reduce GHG emissions is to capture CO₂ from fossil fuelled power stations [4] and other major industrial emitters, to transport it to a site [8] by ship or pipeline [9], and there to inject it into geological reservoirs for permanent storage [5]. This process, is called Carbon dioxide Capture and Storage (CCS). The International Energy Agency (IEA), states that the adoption of CCS technology has the capacity to significantly reduce the amount of CO₂ being released [10][11]. In order to bring CCS to fruition, suitable technologies must be designed, and an appropriate financial model developed. Irrespective of the exact terms of the financial model, it is apparent there will be a requirement for a robust metering technology which can accurately record the mass of CO₂ being transported and injected at every site. From a pragmatic point of view this is required to enable well management and as an aid in determining losses in the transportation chain [12]. From a legal point of view, an EU ETS directive [13] dictates that flow measuring devices must operate within an accuracy of $\pm 1\%$ [14][15]. Taking the UK as a case study, the CO₂ emissions from energy supply sector, that can be used as source points for CCS applications, in the first two quarters of 2016 were approximately 125.8 MtCO₂ [16]. Considering an approximate cost of

5 euros per tonne of captured CO₂ [17], the 1% uncertainty (i.e. ± 1.3 MtCO₂) can cause a total cost of 6.3 million euros. In addition, from the flow measurement point of view, the flow rate of each source is also important to design the metering stations as well as meter selection. The selected single flow meter or metering manifold should cover the flow range of the captured CO₂. For instance, the flow range for industrial scale applications can be as low as 0.2 Mt/y (22,800 kg/h) for a complex ammonia production plant in the minimum production rate to 10.0 Mt/y (1,141,000 kg/h) for a coal-fired power station with oxyfuel capturing system [18].

CCS can learn from the oil [19] and gas industries [20][21][22][23], where CO₂ volume or mass flowrate is measured in connection with for example enhanced oil recovery (EOR) [5][24] and liquefied petroleum gas (LPG), which has approximately similar properties to liquefied CO₂ and has been transported in large volumes over considerable distances [5]. Examples exist for large scale CCS projects. For example, the Sleipner project [25] uses ultrasonic meters [26], while both the In Salah [25] and Vattenfall projects employ orifice plates [26]. The Yates project uses orifice plates supplemented by Coriolis meters and Sheep Mountain project operates both turbine meters and densitometers [26]. It may appear then that the task of choosing mass flowmeters suitable for CCS has already been accomplished; however, there is one major difference between the projects listed above and those of the future: the matter of accuracy. In these earlier projects the operators were not compelled to record the mass flowrate of CO₂ within the bounds determined by EU ETS. Determining the likely accuracy of any particular type of meter under conditions representative of CCS transportation infrastructure [27][28] is the most important consideration of this paper. It has already been suggested that equipment originally developed for oil or gas production wells could be redeployed in CO₂ sequestration wells [29].

In this review paper, the challenges expected for CO₂ transport and metering due to the unusual physical properties of CO₂ containing impurities compared to the other transportable fluids by pipelines, e.g. natural gas, oil and water, are discussed. In addition, existing metering technologies used in other industries, particularly oil and gas, are assessed including accuracy level under conditions representative of CCS transportation infrastructure.

2. Challenges of metering technologies for CCS

2.1. CO₂ phase behaviour

For CCS operations, CO₂ is expected to be transported and injected near the critical point [30] however there is limited experience in accurately metering CO₂ in this condition. To exacerbate the challenge the majority of flow meters currently available are designed to measure flow in one phase only. However, the phase behaviour of CO₂ is unlike that of other transported chemicals; the critical pressure and temperature of CO₂ and CO₂ mixtures are very close to the expected operational pressure and temperature of CO₂ transport pipelines [30][31], see Figure 1. Therefore, small gradient in the pressure and temperature of pipelines can significantly change the physical properties of CO₂ mixtures, which consequently challenge the flow metering. Presence of impurities also can arise two-phase flow in these conditions which also can be another challenge both from the operational and flow measurement points of view [30].

The transport pressure and temperature regions in different phases are shown in Figure 1. Technically, CO₂ with impurities can be transported either in the gas phase or dense liquid / supercritical phase. As in the supercritical phase, CO₂ mixtures have relatively higher densities compared to the gas phase and lower viscosities compared to the liquid phase, transporting in the dense supercritical phase is more desirable from the operational point of view. However, transporting in the dense liquid phase at low temperature conditions and

transporting in the gaseous phase in case of using existing infrastructures for the natural gas transport pipelines is unavoidable. To transport in the supercritical phase, the operational pressure above 8.6 MPa was suggested to ensure operating under single phase conditions [32]. In order to transport in the gaseous phase, the operating pressure must be below 4.8 MPa at temperatures below 20 °C [32].

2.2. Impurities in captured CO₂ stream

CO₂ capture may be associated with different technologies [33] such as post-combustion, pre-combustion and oxyfuel combustion [4][8][34]. Different CO₂ capture processes produce different levels of impurities [35][36][37] (see Table 1). Typically, the concentration of CO₂ will be between 90% and 99% [37][38][39], which may seem very pure; however, phase behaviour and physical properties of highly CO₂ rich fluids are affected by impurities [40][41][42][43][44][45][46]. Figure 2 shows the variation of density of carbon dioxide / nitrogen mixture (95 mol% CO₂ + 5 mol% N₂) as function of pressure at a variety of temperatures using GERG EoS [47][48] by REFPROP v8.0 [49]. Figure 2 also shows the density vs pressure of pure CO₂ at 304.3 K to illustrate the effect of impurities on the density of pure CO₂. The phase envelope for this system (95 mol% CO₂ + 5 mol% N₂) is also given in Figure 3 to show the two-phase region generated by the presence of impurities. It has been reported that the presence of approximately 10% impurities (N₂, H₂ and Ar) can reduce the mixture density, up to 25% in the vicinity of the mixture critical pressure in the supercritical phase [40].

For some metering technologies accurate and reliable density data from Equation of State (EoS) [50] are required in order to obtain the mass flowrate of the cargo fluid, when only the volumetric flowrate is known. Unreliable density predictions will therefore lead to measurement error. Uncertainties around the EoS for mixtures of CO₂ with impurities have

been discussed for classical cubic equations of states, e.g. Peng-Robison (PR-EoS) [51] and Soave-Redlich-Kwong (SRK-EoS) [52], as well as multi parameter equation of state, GERG [40] [41][42][47][48]. In general, the accuracy of these equations in the vicinity of two-phase region would be expected to be weak. Accordingly, Metering techniques based on volumetric flows employing EoS for the density prediction, would have further uncertainties in the pressure and temperature conditions closed to the critical points of the cargo fluid as well as in the vicinity of two-phase region. In addition, the unforeseen presence of water, hydrogen sulphide (H₂S), nitrogen oxide (NO) or sulphur dioxide (SO₂) could produce corrosive products. This will influence the choice of the materials of construction of the flow metering system [2][53]. Moreover, CO₂ hydrates could damage or cause a blockage of flow metering system, which gives rise to operational and safety issues.

2.3. Corrosion and material compatibility

The preferred conditions for cost-effective and safe transport of CO₂ by pipeline is in the dense supercritical phase. The CO₂ stream should kept free of water, sulphur compounds (like H₂S) and oxygen to avoid corrosion [54]. For instance, in existing CO₂ pipelines for EOR, the amount of water must kept below 600 ppm [55][56]. In these conditions, the low amount of water is dissolved in the CO₂ dense phase. The solubility of the CO₂-H₂O system at different pressures and temperatures has been published elsewhere [54][57][58][59]. It should be noted that the solubility of water in CO₂ depends on the temperature and pressure, where lower temperatures reduce the water solubility in the CO₂ stream [60]. During CO₂ transport by pipeline, the temperature can be reduced due to heat transfer from the CO₂ stream to the cold environment. This phenomenon would result in the reduction of water solubility in CO₂ and formation of free water phase. Then, the CO₂ can dissolve in the produced free water phase, reducing the pH of about 3 and producing carbonic acid [54].

The solubility of water in CO₂ is also reduced sharply by increasing pressure up to critical point of CO₂ and then increases slightly with higher pressures. This means free water can also be produced during the pipeline packing [61]. Therefore, flowmeters have to withstand potentially corrosive CO₂ fluids at supercritical conditions, as this may also reduce their accuracy [62]. Generally, flowmeters are constructed of stainless steel (316L, 304L, and super duplex), titanium, nickel alloy C22 or tantalum. In addition, pipelines are lined with a corrosion resistant alloy (CRA), e.g., Tefzel which is similar to Teflon [63][64].

It should also be noted that the impurities in captured CO₂ can also affect the corrosion rate of the materials in the flowmeters. For example, it has been reported that the presence of SO₂ and O₂ impurities increases the corrosion rate of steel in supercritical CO₂ transport pipelines [65][66][67]. Therefore, material compatibility must be carefully selected due to the possible impurities of captured CO₂. Variables to be considered in the material compatibilities include halogen concentration, pH, chemical potential, temperature and pressure [64].

2.4. Measurement uncertainty in CO₂ metering

The measurement uncertainties of metering technologies reported by manufacturers have been mostly determined using fluids such as water or air. The uncertainty of very few metering technologies has been evaluated using CO₂ fluids in the context of CO₂ transport in CCS applications.

The existing NEL's wet gas facility was developed for gaseous CO₂ flow measurement, and orifice plates, Coriolis meter and ultrasonic flowmeters were tested. They concluded that at some of existing metering technologies could be within the CCS uncertainty requirements [68].

The uncertainty of a Coriolis flowmeter has been reported as 0.11% by mass using a rig based on gravimetric calibration at Heriot-Watt University and flowing pure CO₂ in the liquid phase. [22][69]. The performance of the Coriolis flowmeter was also investigated using the same flow rig and in the presence of mixtures of CO₂ and impurities representing the captured streams from pre-combustion, post-combustion and oxyfuel technologies.. Tests were conducted in the steady state and transient conditions at temperature and pressure conditions expected in industrial CO₂ transport pipelines. The absolute average relative deviation (AARD) of 1.0% for pre-combustion and post-combustion fluids was reported, while for oxyfuel fluids were around 1.4%. These studies concluded that uncertainty of Coriolis flowmeters is expected to be within the range of EU ETS requirements of $\pm 1.5\%$ by mass [70].

Experimental studies have also been conducted for flow measurement and leakage detection of gaseous CO₂ at University of Kent using an Averaging Pitot Tube (APT) and a Coriolis mass flowmeter (CMF). Under two-phase CO₂ flow, the APT flowmeter presented a significant error in measuring mass of up to $\pm 25\%$ for a liquid fraction of 20%, while the error for the CMF was $\pm 6\%$ for a liquid fraction of 10%. For binary gaseous mixtures, the error for the CMF was $\pm 1\%$, while that of APT was $\pm 4\%$. Overall, they concluded that both technologies could be deployed in CO₂ flow measurement in CCS transport applications [71].

3. Potential metering technologies for CCS

This review paper specifically discusses the metering technologies [72] available for measuring CO₂ for the purposes of transport for CCS applications. Meters are placed in one of four broad groups (Table 2):

- differential pressure
- velocity measurement

- direct mass measurement
- electrical, magnetic, sonic and radiation technologies

One final group, open channel meters [73], is not considered here because open channel metering generally requires the cargo fluid to be at ambient temperature and pressure.

In this review paper, the terms accuracy, turndown ratio, rangeability, and complexity are defined as follows. Accuracy is the difference between the reading on the meter and the actual flowrate of the cargo fluid expressed in terms of percentage of the meter reading. This will include zero offset error, but does not make any allowance for inaccuracies in converting volume flowrate to mass flowrate (if applicable), nor does it take account of the presence of impurities within the flow, nor of multiphase flow. Turndown Ratio is an expression of the range of flowrates within which an acceptable level of accuracy can be achieved without adjusting or recalibrating the meter. The expression is derived by dividing the maximum flowrate in the acceptable range by the minimum flowrate in the acceptable range. Figures on turndown ratio have been taken from published literature. This was considered to be an acceptable first approximation, however, it should be noted that the error on which the manufacturers base their claims of turndown ratio may be less stringent than what would be required for CCS. Moreover, in most cases commercially available meters measure volume flowrate not mass flowrate so again inaccuracies in converting volume to mass flowrate are not taken into account. The term “rangeability” in flow measurements is defined as the range of the flow rates within the accuracy limits specified for the flowmeter [74]. Complexity of any given mechanical device generally affects its cost to manufacture, its lead time to procure and, perhaps, its fragility. The authors assessed the complexity of each type of meter awarding it a level of 1 to 5, with 5 being the most complex. In order to introduce objectivity in ascribing the level of complexity the authors counted the number of component parts in

each meter type, where the greater the number of component parts, the higher the complexity level.

Table 3 presents a summary of the different existing metering technologies. Each metering technology is analysed in terms of the ranges of operating pressure, temperature and flow rates, with particular emphasis on their applicability in the CO₂ transport metering. In addition, the effect of impurities and composition of CO₂ mixtures on the material compatibility of meters and their expected accuracy level are also summarised. The ability of technologies to be employed in multiphase flow metering, measuring the mass flow rate directly, working in laminar or turbulent flow conditions, surface or subsea environment and compatibility with supercritical CO₂ were stated. Finally, the expected downstream pressure drop in the meter, accuracy level, turndown ratio and complexity level are also compared.

3.1. Differential Pressure Technology

This group includes orifice plate, Venturi and variable-area flow meters (Table 2). The operating principle is to measure the pressure drop across a restriction and to use this to calculate the fluid's velocity and hence its volume flowrate. Mass flowrate can then be determined using a reliable EoS.

3.1.1. Orifice Plate [75]

Orifice plate meters are commonly used to measure volumetric flowrate of a single phase and steady flow, for example when large volumes of gas are to be delivered for commercial purposes [76]. The working principle is to measure pressure drop before and after an orifice plate [76][77], so volume flow rate can be calculated knowing fluid density, cross sectional areas of the pipe upstream and area of hole in the orifice plate. In order for orifice meters to provide reliable results, a fully developed flow is required. The simplest means of achieving this is by ensuring that the meter is located in a section of the pipe which has a straight length

before and after the meter. Baker [72] recommends an upstream straight pipe run of between twenty to forty pipe diameters, other authors recommend different values [14]. Where it is not possible to include a long length of straight pipe ahead of the meter, then the use of a flow conditioner [76] may be considered. This will add to the cost of the system. One of the major disadvantages of using orifice plates is that, as a result of energy loss due to turbulence in the fluid passing through the orifice [73][76][78] a permanent pressure drop [72] may occur such that:

$$\Delta P_p = \Delta P_i (1 - 0.24\beta - 0.52\beta^2 - 0.16\beta^3) \quad (1)$$

where ΔP_p is the pressure drop downstream of the plate, ΔP_i is the pressure drop across the orifice plate, and β is the ratio of the hole in the orifice plate and cross sectional areas of the pipe upstream. The permanent pressure drop is of particular concern for CCS as CO₂ will be injected in a dense liquid or supercritical form and, as previously stated, the reduction in pressure might lead to phase transition from liquid phase to gaseous state. The effect of the presence of impurities depends on the type and level of concentration of impurities and this can also lead to two-phase flow conditions. In this event, the density of CO₂ mixtures rapidly changes resulting in unreliable flow measurement. Other disadvantages of orifice plates are that these are maintenance intensive [14] and have a limited turndown ratio – typically 3:1 to 5:1 [14]. The advantages of these meters include that they can be used in liquid and gas applications and can withstand extreme temperature and pressure conditions. The accuracy of the meter is approximately 1.5% of volumetric flowrate [14].

Orifice plates offer a relatively cheap and robust means of measuring volume flowrate of a homogenous, single phase, contaminant-free liquid (See Table 3). However, in the context of transport of CCS systems where multi-phase, multi-component fluids may occur, orifice

meters could not provide measurements of the mass flowrate of CO₂ with the accuracy required to meet the expected financial models.

3.1.2. Venturi Meters [75][79]

Venturi meters work on the same principle as orifice plates [79]; however, their geometry is quite different, as described here. The Venturi meter has three main parts, namely: (i) the acceleration cone [80] whose inlet diameter matches the bore of the upstream pipe and then reduces, typically at an angle of 21° [80] ±2° [81] to a diameter of between $\frac{1}{3}$ and $\frac{3}{4}$ times the pipe's inside diameter (ID) [81]; (ii) the middle, or throat, section [81] whose bore remains constant, and whose length is generally equal to the bore [73]; and (iii) the deceleration cone [80] where the bore increases, typically at an angle of between 5° and 15°, [80][81] normally regaining the same bore as the upstream pipe [82]. Pressure measurements are taken both at a point upstream of the constriction, and also at the narrowest point of the device. Venturi meters are robust and relatively low cost but they can produce a permanent downstream pressure drop [14]; however, this can be mitigated by careful design [81]. A carefully calibrated Venturi meter can give a turndown ratio of 9:1. Graebel [81] provides an equation which allows to calculate the velocity of the cargo fluid, provided that the upstream and throat cross sectional areas and pressures are known, resulting in estimates of volume flowrate to within 1 to 3% provided that the pressures can be measured accurately and that the Reynolds number for fluid at the inlet is greater than 10^5 .

Like orifice plates, Venturi meters offer a relatively cheap and robust means of measuring the volume flowrate of a homogenous, single phase, contaminant-free liquid. Venturi meters have an advantage over orifice plates in that they can provide larger turndown ratios and lower downstream pressure drops. However, they suffer many of the same disadvantages as

orifice plates: in that they are not suitable for multi-phase, multi-component fluids, and they may require a long, straight run upstream pipe runs [14][80][81] (See Table 3).

3.1.3. Variable-Area Flowmeters

Variable-area flowmeters, also called rotameters, consist of a length of vertically oriented pipe which tapers outward from bottom to top and which has a float inside [83][84]. Fluid is introduced at the bottom, and exits at the top. The greater the volume flowrate, the higher the float will rise. The float height is dependent on the velocity of the fluid, and the buoyancy and the mass of the float [80]. Variable-area flowmeters provide good turndown ratios (as high as 12:1 [14]). Accuracies of as high as 1.5% (gas) and 0.3% (liquid) [14] of full-scale flow would be possible provided that the meter was calibrated for CO₂ at a particular temperature and pressure. However, the floats have been known to stick [81], they are not suited for multi-phase fluids (See Table 3), and their design makes them unsuitable for a subsea environment so ruling them out for the use of subsea sequestration wells.

3.2. Velocity Measurement Technology

Velocity flowmeters are a diverse group measuring flowrate by determining the velocity of the fluid at one or several points within the pipe's bore, making an approximation the cross-bore flow profile, and from this calculating volume flowrate (Table 2). The principle is the same for all of these meters but the technologies used to determine the fluid velocity profile are very different.

3.2.1. Pitot Tubes

The principle of the Pitot tube is that it converts the kinetic energy of a small portion of the cargo fluid into potential energy. In simple terms, an L-shaped tube is integrated into the conduit such that the open end of the horizontal leg points into the oncoming fluid, while the vertical arm penetrates the wall of the pipe. Static pressure is obtained by determining the

pressure at the inner wall of the pipe via a tapping through the pipe's wall. The pressure generated within the Pitot tube is known as the stagnation pressure. If the stagnation pressure is compared to the static pressure then the velocity of the fluid can be determined using the equation [81]:

$$V^2 = 2 \times (P_{stagnation} - P_{static}) / \rho \quad (2)$$

Where ρ is the fluid density. Graebel [81] cautions that if the Reynolds number of the cargo fluid is below 10^5 then formula (2) above will overestimate the fluid's velocity. Readings from the Pitot tube represent the fluid flow at a single point. Typically the maximum fluid velocity will be found at the pipe's centre. If the flow is known to be turbulent then Overbeck et al. [76] suggest that multiplying the maximum velocity by a factor of 0.82 will give a reasonable approximation of the mean flow. Alternatively, since the mean fluid velocity theoretically occurs at a point approximately $0.75 \times$ pipe's inner radius [76], a single tube positioned at this position would give an approximate mean velocity [73]. More accurately the annular uses multiple tubes to determine the flow profile over the pipe's cross section [72]. The accuracy of this method ranges from 0.5% to 5% full scale (FS) and its turndown ratio is 3:1 or even up to 4:1 [85].

The Pitot tubes meet many of the requirements for CO₂ CCS metering, as they can cover the ranges of volume flowrates, pressure and temperature expected of the CO₂ cargo fluid. In addition they can be manufactured from corrosion-resistant materials and made suitable for subsea applications. However the devices will have to be carefully designed in order to prevent significant systemic errors [80][86], they are likely to require in-situ calibration [73] and they cannot provide an accurate measure of volume flowrate, even in single phase single constituent flow, without adding considerable complexity. In addition, they cannot provide direct mass flow measurement and are not suitable for multi-phase flow (See Table 3).

3.2.2. Vortex Flowmeters [86]

Vortex shedding can occur when a non-streamlined object, a “bluff body”, is placed in the path of a fast flowing fluid. Eddies will be produced at the edges of the body [80][86] and as the eddies move downstream they become larger and eventually break away from the bluff body. Immediately another eddy will start to form on the opposite downstream edge [50]. The frequency of vortex shedding is directly proportional to the velocity of the cargo fluid, but independent of fluid’s viscosity and density [80][86]. Experiments have shown that the Strouhal Number, (a dimensionless number which relates diameter of the bluff body, and the velocity of the fluid to the frequency at which the eddies are shed) remains between 0.20 and 0.21 provided that the flow has a Reynolds number of between 300 and 48,000. The range of Reynolds number would be typically on the order of 10^6 in turbulent regime [87]. The viscosity range depends on the phase, operational pressure and temperature, as well as the type and concentration of impurities. In the gas phase, the viscosity of 10-25 $\mu\text{Pa}\cdot\text{s}$ and in the dense liquid / supercritical phase would be in the range of 50-150 $\mu\text{Pa}\cdot\text{s}$ [40].

Reynolds numbers drop as viscosity rises, with the maximum acceptable viscosity being somewhere between 8 and 30 cP. For Reynolds numbers of 10,000, the meter’s accuracy may be as poor as 10% of the real flow [14]. However, when liquids are of low viscosity, it is possible to operate with Reynolds numbers in excess of 30,000, accuracies of between 2% (gas) and 1.5% (liquid) [14] and turndown ratios of 20:1 [14].

Vortex meters measure the frequency of the reversal of a bluff body’s lateral displacement. By taking simultaneous readings of frequency and of the strength of the displacement force, modern vortex meters can determine mass flowrate, not just volume flowrate. More sophisticated vortex flowmeters are fitted with temperature and pressure sensors allowing automatic adjustments to be made for variations in thermally dependant fluid properties, so improving inaccuracies in the measurement of mass flowrate to as little as 1.25% [14].

Because of the vortex meter's inability to distinguish between phases, e.g. gas bubbles within the liquid phase, accuracy will drop if two phase flow is encountered. For vortex meters, permanent pressure drops downstream of the meter have been found to be around half of that of an orifice meter under similar circumstances [14]. They have low sensitivity to changes in fluid flow characteristics, exhibit little wear even after long term use, and their purchase and maintenance costs have been found to be low [15]. These meters come in sizes suitable for pipe up to 12 inches bore, and can be adapted for use with hazardous chemicals. In commercially available vortex meters the oscillations of the bluff body are typically registered using capacitance or piezoelectric sensors located inside or outside the body of the flowmeter.

Vortex flowmeters are, as yet, unproven for the measurement of the flowrate of CO₂ in a supercritical phase. However, this metering technology may be considered for CCS transport applications, provided that the injection fluid is high purity CO₂, and provided that the fluid is maintained in a supercritical phase (See Table 3).

3.2.3. Calorific Flowmeters [88]

In calorific flowmeters two probes are inserted through the wall of the pipe and into the flowing fluid. The probes are placed in close proximity, but are located in such a way that there is no possibility of heat transfer between them. As the cargo fluid passes over the warmer probe the tendency is that it would be cooled.

This principle has been utilized in two different ways, either by dictating the temperature of the probe and supplying whatever current is required in order to maintain the temperature [80][88] (constant temperature mode) [81], or by keeping the supply current the same and measuring the probe's resistance due to changes in its temperature (constant current mode) [81]. Since neither the current nor the resistance vary linearly with the fluid's velocity an

electronics package is required in order to turn the non-linearity of the raw data into a linear output [81]. Calorific flowmeters can achieve high turndown ratio of 100:1, high accuracies at low flowrates, and their response time depend on the thermal conductivity of the fluid. The thermal properties of the fluid depend on pressure, temperature, and composition. However, as the variation of thermal properties due to pressure and temperature are typically small, the impurities can then cause a significant error in the measurements. Therefore, calibration is required for calorific flowmeters according to the composition of the fluid, and hence, the application of this flowmeter for the CCS application is associated with uncertainties [89].

Other factors must also be considered: calorific flowmeters could not handle the volume flowrates expected, and they are fragile[80][81]. They cannot provide a direct measurement of mass flowrate, and they are unsuitable in multi-phase and multi constituent flows (See Table 3). While some of these issues could be overcome with careful management of the cargo fluid, and by providing a bespoke design of meter, it is considered that have too many disadvantages to be considered for CCS applications.

3.2.4. Axial Turbine Flowmeters

Axial turbine flowmeters act by placing the turbine within the flow stream of the cargo fluid and allowing the fluid to turn the impeller. The rate of rotation of the impeller, which is directly proportional to the fluid velocity, is detected by a pickup (flow sensor), usually a magnetic type [80]. Theoretically, the rotational velocity of the impeller is directly proportional to the velocity of the fluid [81], thus the volume flowrate can be calculated from the rotational speed of the impeller and the cross sectional area of the pipe. Turbine flowmeters are most suitable for fluids with low viscosities. Although accuracies in the range $\pm 0.05\%$ have been claimed [80], typical values are 1.5% for 0-20% of the maximum measurement range for gas phase and 0.3% for 20-100% of the maximum measurement range

for liquid phase [14]. Turndown ratios up to 10:1 are possible at higher flowrates [80]. Turbine flowmeters have the advantage over positive displacement meters that they allow higher flowrates, and have a smaller non-recoverable pressure drop. Depending on the impeller material, they can be suitable for corrosive environments, and for high temperature applications. There are disadvantages inherent in this type of meter; however, as they need upstream and downstream flow conditioning, including filtering of the cargo fluid if particulate matter is present. In addition, they require frequent calibration, and are sensitive to both vibration and flow profiles.

Axial turbine flowmeters are already available which could match the basic physical parameters (volume flowrate, size of pipe, temperature, pressure, contaminants) of the expected fluid flow (See Table 3). However, axial turbine flowmeters share the inherent disadvantages of the lower complexity technologies (complexity 3 and below), as they cannot provide direct measurement of mass flowrate, and they are not suitable for multi-phase, multi constituent flow. Wenzel [80] noted that this type of meter is not suitable if slugs of fluid are present in a gaseous cargo fluid (a situation which may be envisaged if the physical properties of the CO₂ are not rigorously maintained), as these might overspeed the rotor. When this is considered in conjunction with the facts that axial turbine flowmeters are relatively complex (rated 4) and are not suitable for subsea use, then this technology may not be feasible for CCS transport applications.

3.3. Direct Mass Measurement Technology

Mass flowmeters, also known as inertial flowmeters, measure the mass flow rate of the cargo fluid employing different technologies. This group of meters includes Coriolis meters, Rotary Vane Flowmeters, Geared Impeller flowmeters and Hastings meters, as described below.

3.3.1. Coriolis Meters [22][90][91]

Coriolis meters work on the principle that liquid flowing through a U-shaped vibrating tube will cause the tube to twist. The amount by which the tube twists is affected by frequency and amplitude of the vibration of the tube, and the mass flowrate of the cargo fluid [21]. They are robust, an important consideration where of two phase flow or slugging is expected. Coriolis meters can allow for the cargo fluid being a mixture of liquid and gaseous CO₂, but they cannot account for contaminants. For instance, if water were present, the mass flowrate recorded by the Coriolis meter would be the total mass flowrate of fluid; it would not discriminate for the volume fraction of CO₂. This would not necessarily present a problem, provided that the volume fraction of the contaminant was a few percent. In order to transport large quantities of CO₂ expected in CCS projects pipelines of at least 12 inches bore are likely, and pipe diameters of 40 inches are not inconceivable. This will limit the selection of flow meters as Coriolis meters are generally available for pipe diameters of up to just 6 inches with 12 inch meters only recently becoming available.

In summary, Coriolis meters offer great promise for CCS applications. The main disadvantages of this technology are that it is complex and not yet proven for the measurement of CO₂ in a supercritical phase at the mass flowrates required for CCS (although see Lin et al. [22] for laboratory scale calibration). Due to absorbance characteristics of supercritical fluids, supercritical CO₂ can degrade and affect different types of materials [26]. In addition, meters are not yet available in the sizes likely to be required. Other challenges, such as the inability of Coriolis meters to discriminate the volume fraction of CO₂ in a multi-constituent cargo fluid, and the reliance on accurate equations of state to convert from volume flowrate to mass flowrate measurements (See Table 3) could be overcome by careful management of the purity and physical state of the cargo fluid.

3.3.2. Rotary Vane Flowmeters [76]

Rotary vane flowmeters generally have cylindrical bodies which contain a multi-vane rotor, where the vanes are equally spaced. The tips of each vane touch the inside of the meter's housing. As the vane rotates, fixed packets of fluid of identical volume move around the central axis of the rotor. Fluid is introduced into the lowermost compartment of the meter, the force of the flow causing the vane to rotate. Sensors counting the number of rotations of the vane can then determine the total volume of fluid to have passed through the meter.

Although rotary vane meters are widely utilized in flow measurement due to their accuracy and reliability, their high sensitivity to the change of fluids' density and viscosity make them unsuitable for use in CCS transport applications [92] (Table 3).

3.3.3. Geared Impeller Flowmeters [76]

Geared Impeller Flowmeters have two figure of eight rotors which are interconnected such that the lobe of one fits within the waist of the other. The rotors are encased within a body, the rotors' tips being in close contact with the inside of the body, the rotors turn on axels which lie parallel one to another. Fluid enters the gap between the rotors causing them to turn, a fixed volume of fluid being transported with each rotation. Geared impeller flowmeters combine the same advantages and disadvantages described above for rotary vane flowmeters (Table 3).

3.3.4. Hastings Meter [81]

The principle behind the Hasting's meter is heat transfer to a moving fluid. The meter features a small capillary tube, typically 1mm inside diameter, attached to the main pipe in such a way as to provide a bypass for a small amount of cargo fluid. An electric coil surrounds the tube, heating it with a constant heat flow. In a moving fluid a thermal gradient is achieved, the temperature of the fluid exiting the capillary being higher than the

temperature of the fluid entering. The temperature gradient is proportional to the mass flowrate of the fluid.

This meter boasts mechanical simplicity; however, it is only suitable for low mass flowrates as it takes time for the fluid within the capillary to heat up. In addition the small diameter pipe can become blocked by dirt derived from erosion / corrosion of the pipeline. Moreover, this type of meter is not suitable if gas bubbles are likely to be present. In addition, if the CO₂ transported in the liquid phase is closed to the phase boundary, the pressure drop along the pipeline can result in two-phase flow. The flow regime in this condition would be bubble flow which contains gas bubbles in continuous liquid phase. Therefore, this type of meters is not applicable for multiphase CO₂ transport (See [Table 3](#)).

3.4. Electrical, Sonic and Radiation technologies

These metering technologies are based on signal processing methods, where some properties of flow, e.g. velocity, are measured by two identical sensors installed at two known locations of the pipeline.

3.4.1. Radiation Attenuation Densitometry [\[93\]\[94\]](#)

Radiation Attenuation Densitometers (RAD) meters are commonly used in the oil industry to measure oil produced from individual wells and also to measure and record water and gas injection [\[95\]](#). The principle behind RAD is that different chemicals absorb radiation at different frequencies. This remains true whether the fluid is in gaseous or liquid form. RAD can, therefore, record mass flowrate of a cargo fluid which is a mixed phase and/or made up of more than one constituent [\[35\]](#). This ability of any given substance to absorb energy is given by the Radiation Attenuation Coefficient (RAC). A radiation emitter is placed on one side of the pipe and a radiation detector at the other. If the energy and frequency of the emitted radiation are known, and the radiation received at the detector accurately measured,

the data can be analysed to determine what constituents are present in the flow stream. By repeating the process several times a second a picture of the mass flowrate can be built for each of the components of the cargo fluid [35]. When two comingled fluids have very different RACs, then it is possible to use this to determine what percentage of mass flowrate of a given cargo fluid can be attributed to each constituent. This works very well for H₂O/hydrocarbon mixtures; however, for CCS projects, the fluid of interest will be CO₂ in a liquid/dense or supercritical condition which may carry contaminants with RACs similar to that of CO₂ making it difficult to distinguish the contribution of CO₂ to the overall mass flowrate versus that of the contaminant.

RAD is complex, expensive and not yet proven for measuring CO₂ in a supercritical state, although it would meet other requirements for transport in CCS applications (See Table 3). These types of meters have a proven track record in fiscal metering systems in the oil and gas industry and could become a strong contender for CCS transport applications.

3.4.2. Tomography [96]

One of the challenges of measuring multiphase and/or multi-constituent fluid flow is that the flow regime can change within a very short time and over a very short distance. Whereas RAD can be used to determine the mass flowrate of individual constituents within a cargo fluid, tomography can provide information about the flow regime in real time [60]. The process of measurement requires that the source and receiver are moved relative to each other allowing the radiation to be focused at various points through the pipe, and therefore, creating a 3D image of the flow [72]. The advantage of tomography for CCS application is to be able to measure mixed, two phase flow at high mass flowrates and gives a real time mass reading of flow regime. Most forms of tomography use a radiation source (x-rays or γ -rays) which may raise safety concerns. However, other variants like Electrical Capacitance Tomography

(ECT) and Electrical Resistance Tomography (EDT) measure changes in the electrical properties of the cargo fluid, and therefore, do not require radiation sources [97]. Like RAD, tomography is complex, expensive and not yet proven for measuring CO₂ in a supercritical state. Again, like RAD, tomography meets all of the other requirements for CCS transport applications (See Table 3). Unlike RAD, tomography does not have the same history of use in similar applications and as such it is likely that it would require more development than RAD before it could be deployed for CCS transport applications.

3.4.3. Ultrasonic Meters [98][99]

Ultrasonic flowmeters measure variations in the transit time of an ultrasonic pulse through the cargo fluid. Alternatively, they can measure variations in the frequency with which a reflected ultrasonic pulse is received. The speed of sound in a fluid is not constant and it varies with density, and hence, with temperature and pressure. However, provided that these physical parameters are kept constant, it is possible to use either time of flight (TOF) or frequency to measure fluid velocity. In their simplest form, TOF (also known as transmission) meters have two transducers which are placed either in the fluid stream (wetted) or external to the pipe's bore (non-wetted). An ultrasonic pulse emitted from the downstream transducer is received by the upstream transducer and the time noted. A burst of ultrasound sent from the upstream transducer is picked up by the downstream transducer and the time measured is affected by the velocity of the cargo fluid. A burst travelling in the same direction as a moving cargo fluid will take a shorter time to move between the transmitter and the receiver than it would in static fluid, while a burst travelling against the direction of flow will take longer. When fluid temperature and density are known, manufacturers claim an accuracy of $\pm 1\%$ [78] and other literature puts the figure at 0.5% for both liquid and gas [14]. Where the transducers are external to the pipe signal attenuation due to air spaces, the use of a pipe liner can significantly decrease the accuracy of the flowmeter. Inconsistencies can also

occur with non-wetted transducers, where the pipe is to be manufactured from stainless steel. Single beam meters, i.e. one pair of transducers, have been used in the past but more recent developments have included multi-path meters with the transducer pairs arranged to give across the pipe horizontally or radially. This significantly increases the accuracy of the meter. Transit time meters have been used to measure flowrates of liquid N₂, liquid Ar and liquid He. This may indicate that they can be used for measuring the flow of liquid CO₂, although in previous applications the liquid gasses appear to have been in a cryogenic state.

Ultrasonic meters are not as well matched to CCS applications as either RAD or tomography that can provide direct mass flowrate measurement and can generally discriminate between CO₂ and other constituents in a mixed flow (See [Table 3](#)). Ultrasonic meters are of equivalent complexity to both RAD and tomography meters, and they are very likely to require considerable development in order to be suitable for CCS transport applications. Ultrasonic metering is, therefore, not preferred to RAD or tomography for CCS.

3.5. Meters in Combination – Multiphase Flowmeters [\[100\]](#)

This paper has considered the use of single types of meter in isolation, but the oil industry uses multiphase flowmeters (MPFM) which are, effectively, two types of meter in combination [\[101\]](#). Hasebe et al. [\[101\]](#) looked at the accuracy of commercially available MPFMs for measuring produced fluids from wells containing water, oil and gas in various combinations. Four types of meters were tested, with each combination containing a Venturi meter in addition to one of the following: gamma densitometer, positive displacement, electrical impedance tomography or microwave tomography. All MPFMs were reported to have an accuracy better than 5% within their optimum operating envelope. It was noted that accuracy declined significantly when the gas volume fraction (GVF) rose above 88% [\[101\]](#).

However, as in CCS transport the gas level is expected to be very small, MPFMs are not likely to be deployed.

The two-phase CO₂ injection into the Yates Field in West Texas started in 2004, and initially, orifice meters were used to measure the injected two-phase CO₂ with a reported error of up to 80% [102]. Coriolis flowmeters were then installed and the measurement uncertainty was improved significantly to 5% by mass. However, this value is notably higher than the 2% uncertainty requirements stated by UK APGTF [103]. It should be noted though that metering two-phase flow is challenging, and new technologies, for instance combination with tomography techniques, could improve the uncertainty of flow measurement for multiphase CO₂ applications [26].

4. Conclusions and Recommendations

This paper reviews the capabilities of existing metering technologies (Table 3) which could potentially be used for CCS transport operations.

It seems clear that there is no current single metering system which can, on its own, fulfil all of the requirements for metering CO₂ in CCS. It is apparent that some technologies, such as orifice plate meters, which are well proven in other applications (generally the least complex and best understood types of meters) are unsuitable for CCS due to uncertainties around EoS [68]. This is further complicated by, in some instances, significant changes in the physical condition of the fluid caused by the measurement device itself. When considering the added complexity of the presence of contaminants, the simpler metering systems, such as turbine meters, would not work, and could not be modified to work in the CCS environment. There are three technologies then that can be considered, namely Coriolis, RAD and Tomography. Learning from the experience of Hasebe et al. [101], it seems likely that a combination of metering types, optimized for CCS, may be necessary in order to achieve the levels of

accuracy desired. The accuracy level required by the EU ETS is $\pm 1.5\%$ by mass. Combination of flowmeters are mostly suitable for the multiphase flow conditions, particularly when the free water phase is available, or implications in EOR and re-cycling the CO₂ during the process of EOR.

In order to accelerate commercialization of existing metering technologies for CCS transport applications, a regulatory framework based upon measurement confidence is needed. Therefore, further studies and developments for evaluating these metering technologies for dense liquid / supercritical CO₂ are a priority in order to identify the best performance meter suitable for CCS transport operations.

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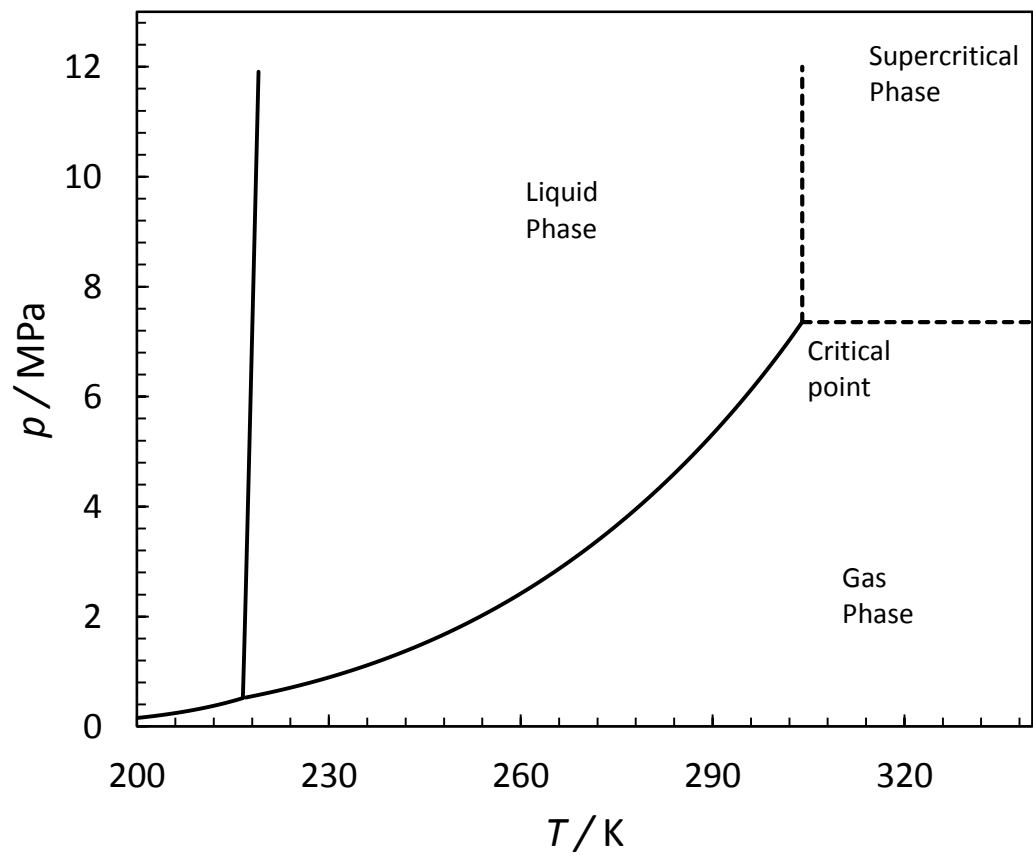


Figure 1. Phase diagram of pure carbon dioxide (created using REFPROP v8.0) [49]

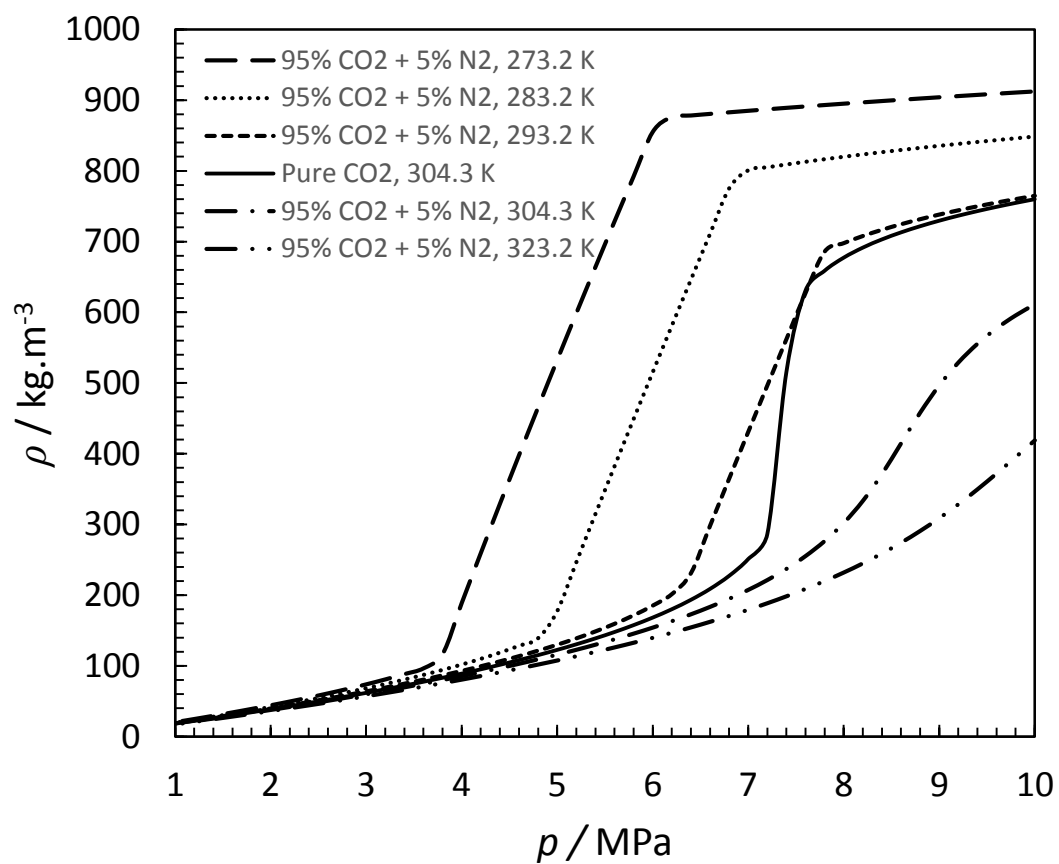


Figure 2. Densities of 0.95 CO_2 + 0.05 N_2 as function of pressure at a variety of temperatures

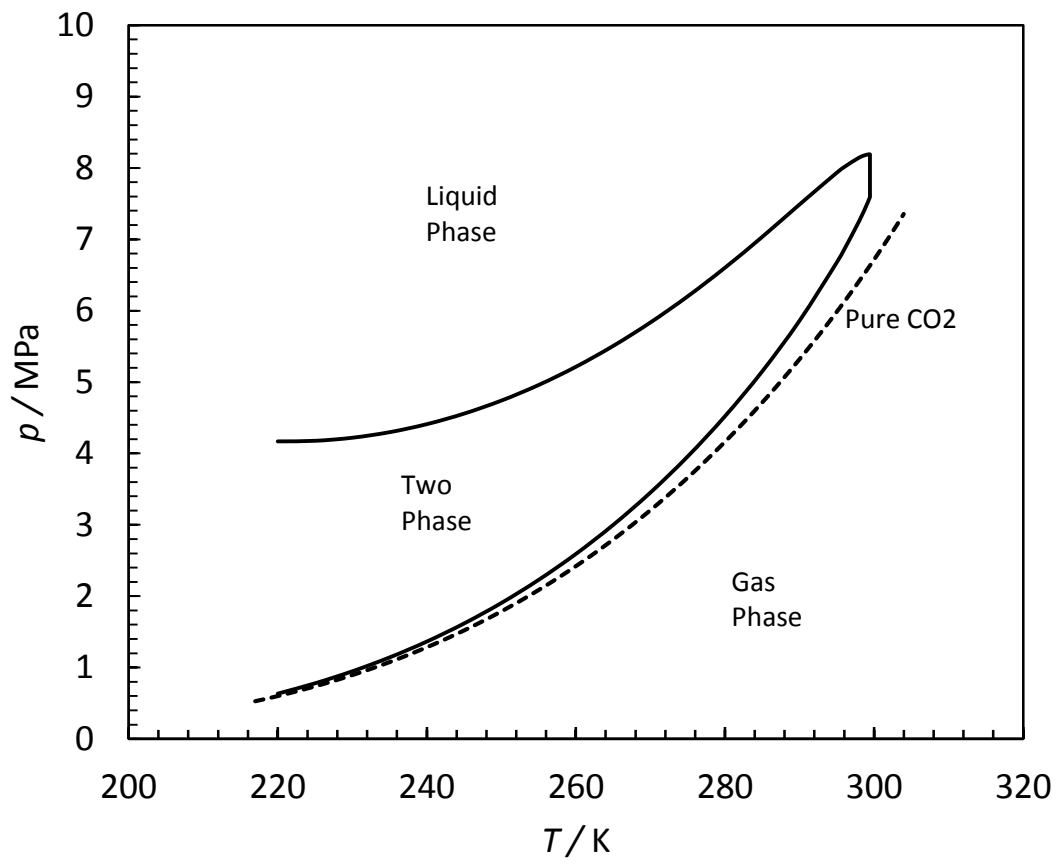


Figure 3. Phase envelope for 0.95 CO₂ + 0.05 N₂ [49]

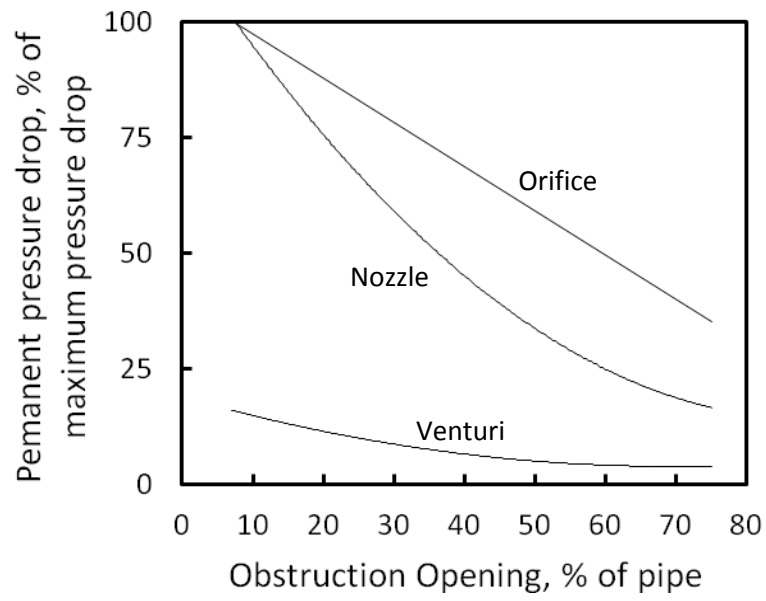


Figure 4. Permanent pressure drop as function of obstruction opening for different technologies [104]

Table 1. Potential impurities of CCS streams from the three different capture technologies
[\[20\]](#)[\[33\]](#)[\[35\]](#)[\[36\]](#)[\[37\]](#)[\[105\]](#)

Compositions	Post-Combustion (Scenario 1) ²⁹	Post-Combustion (Scenario 2) ²⁹	Pre-Combustion	Oxyfuel
CO ₂	95.5 wt %	99.4 wt %	> 95.6 vol%	> 90 vol%
CH ₄	-	-	< 350 ppmv	
N ₂	-	-	< 0.6 vol%	< 7 vol%
H ₂ S	-	-	3.4 vol%	Trace
C ₂₊	-	-	< 0.01 vol%	-
CO	-	-	< 0.4 vol%	Trace
O ₂	-	-	Trace	< 3 vol%
NO _x	NO ₂ 44 ppmw	NO ₂ 10 ppmw	-	< 0.25 vol%
SO _x	SO ₂ 4.4 wt%	SO ₂ 0.6 wt%	-	< 2.5 vol%
	SO ₃ 579 ppmw	SO ₃ 42 ppmw		
Ar	-	-	< 0.05 vol%	< 5 vol%
HCl	875 ppmv	36 ppmv	-	-
Hg ²⁺	261 ppbw	23 ppbw	-	-

Table 2. Broad groups of potential metering technologies for CCS

Metering technology group	Description
Differential pressure technologies	Measuring the pressure drop resulting from the cargo fluid passing through a restricted passage, an example would be orifice plate meters.
Velocity measurement	Measuring the velocity of the cargo fluid directly by placing a probe of some sort within the flow of the cargo fluid. Devices falling into this category are diverse but may include equipment such as turbine meters and vortex detection meters.
Direct mass measurement	Measuring the mass of the cargo fluid passing from a fixed point of the device per unit time, an example would be Coriolis flowmeters.
Electrical, Magnetic, Sonic and Radiation technologies	This is a rather non-homogenous group covering metering technology as diverse as Doppler Effect and Radiation Attenuation Densitometry.

Table 3. Summary of existing metering technologies for metering CO₂

PERFORMANCE PARAMETERS	FLOWMETER TYPE											
	Orifice Plates	Venturi	Variable Area	Pitot Tube	Vortex	Calorific	Turbine	Coriolis	Radiation Attenuation Densitometry	Tomography	Ultrasonic	Hastings
Volume Flowrate Compatible With CO ₂ Injection Rates? (0.0138 m ³ /s 10 000 bbl/d) 1	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Temperature Range of Meter Compatible With CO ₂ Injection Rates? (4 to 40 °C) 2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pressure Range of Meter Compatible With CO ₂ Injection Pressures? (15 MPa) 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Materials Compatible With Composition of Injected CO ₂ ? 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Size Range Compatible With CO ₂ Injection Rates? (12" ID pipe and 6" ID pipe) 5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Direct Mass Flowrate Measurement? 6	No	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes
Multi-Phase? 7	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	No
Can Discriminate CO ₂ in a Non-homogeneous Cargo Fluid? 8	No	No	No	No	No	No	No	No	Yes	Yes	No	No
Permanent Downstream Pressure Drop?	Yes	Yes	Yes	No	Yes	No	Yes	No	No	No	No	No
Turbulent or Laminar Flow	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar	Laminar	Both	Both	Both	Laminar
Accuracy 9	1.5% Gas 1.5% Liquid	1.5% Gas 1.5% Liquid	1% of FS	Unknown	2% Gas 1.5% Liquid	Unknown	1.5% Gas 0.3% Liquid	1% Gas 1% Liquid	Unknown	Unknown	0.5% Gas 0.5% Liquid	Unknown
Turndown Ratio	3:1 to 5:1	09:01	12:01	Unknown	20:01	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Measurement Accuracy Immune to Changes in Physical Properties?	No	No	No	No	Yes	No	Yes	Yes	Yes	Yes	No	No
Surface or Subsea Applications?	Both	Both	Not Subsea	Both	Both	Not Subsea	Not Subsea	Both	Both	Both	Both	Both
Proven for CO ₂ in a Supercritical State?	Yes	Yes	No	No	No	No	No	No	No	No	Yes	No
Complexity (high = 5, low =1) 10	1	1	2	3	2	3	4	5	5	5	5	3

1. Assumed from the injection rates of produced water into Federal UIC Class II wells (between 1,000 and 26,000 bbl/day)

2. Min assumed from the temperature of seawater around the wellhead. Max assumed from max temperatures expected on land due to sunshine.

3. Critical point pressure of CO₂ is 7Mpa, intention is to keep CO₂ within supercritical or liquid phases. Assumption is made that cargo fluid will be maintained at 2 x critical point pressure to allow a margin
4. It is assumed that in the worst case the cargo fluid will be corrosive due to the presence of trace amounts of water and/or hydrogen sulphide and/or sulphur dioxide.
5. It is assumed that the CO₂ will be transported via new bespoke optimised diameter pipelines
6. Are the meter readings dependant on fluid density? Is this factored in when the meter provides its reading?
7. Not multi-component but multi-phase. This is important if the CO₂ drops below the critical point values.
8. This may be important if the CO₂ is not clean, for instance if water is present or N₂
9. The term accuracy is meant to describe the meter's ability to measure volume flowrate of a single phase single component cargo fluid
10. Complexity is based on the number of parts