The challenges of designing a custody transfer metering system for CO_2

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1 INTRODUCTION

During the Paris climate conference (COP21) in December 2015, over 190 countries agreed to limiting global warming to well below 2°C, and to pursue efforts to limit it to 1,5°C. There are many different ideas on how to achieve these goals, for example the Rapid and Net Zero scenarios per BP Energy Outlook 2020.

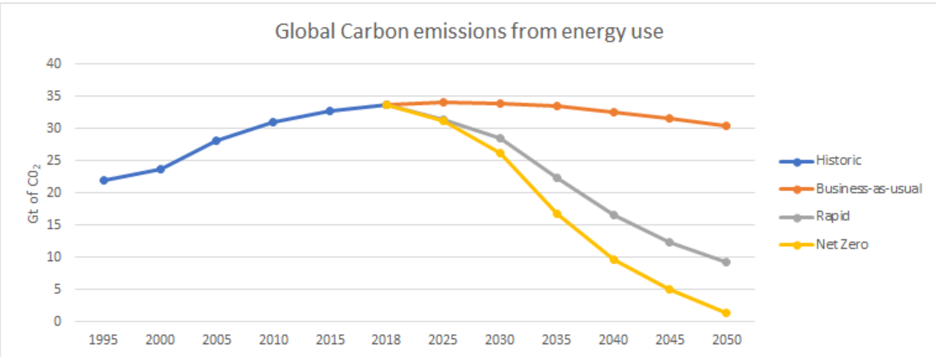

Fig. 1 – Energy related CO_2 emission per BP Energy Outlook 2020[1)]

In both the Rapid and the Net Zero scenario, most of the CO_2 reduction is realized by increased efficiency and a change in the energy mix. A substantial role is however also envisioned for CCUS (Carbon Capture, Usage, and Storage); by 2050 the annual storage of CO_2 is expected to be 3,9 Gt in Rapid and 5,4 Gt in Net Zero according to the BP 2020 energy Outlook. To put this in perspective; 3,9 Gt of liquid CO_2 equals a volume of ~ 65 MMBPD.

As a result, the number of CO_2 capture and storage (CCS) projects and the number of countries implementing CO_2 trading schemes is expected to grow significantly over the next years. Accordingly, the number of research initiatives on CCS, for example the Norwegian NCCS research center, has increased significantly in recent years. With CCS, also the need for Custody Transfer and Fiscal metering arises. For instance, producers need to report the amount of CO_2 that was captured, and storage facilities need to know what to invoice to their CO_2 suppliers. In this paper we investigate the regulatory requirements and the technical challenges regarding fiscal and custody transfer of CO_2.

2 CARBON PRICING AND REGULATORY REQUIRMENTS

There are two main types of carbon pricing: carbon taxes and emissions trading systems (ETS). A carbon tax sets a price on carbon by defining a tax rate on greenhouse gas emissions or, more commonly, on the carbon content of fossil fuels. An ETS caps the total level of greenhouse gas emissions and allows industries with low emissions to sell their extra allowances. By creating supply and demand for emissions allowances, an ETS establishes a market price for CO_2 emissions. Per figure 2 there are currently 64 carbon pricing schemes in place, covering slightly over 21% of global GHG (Green House Gases) emissions.

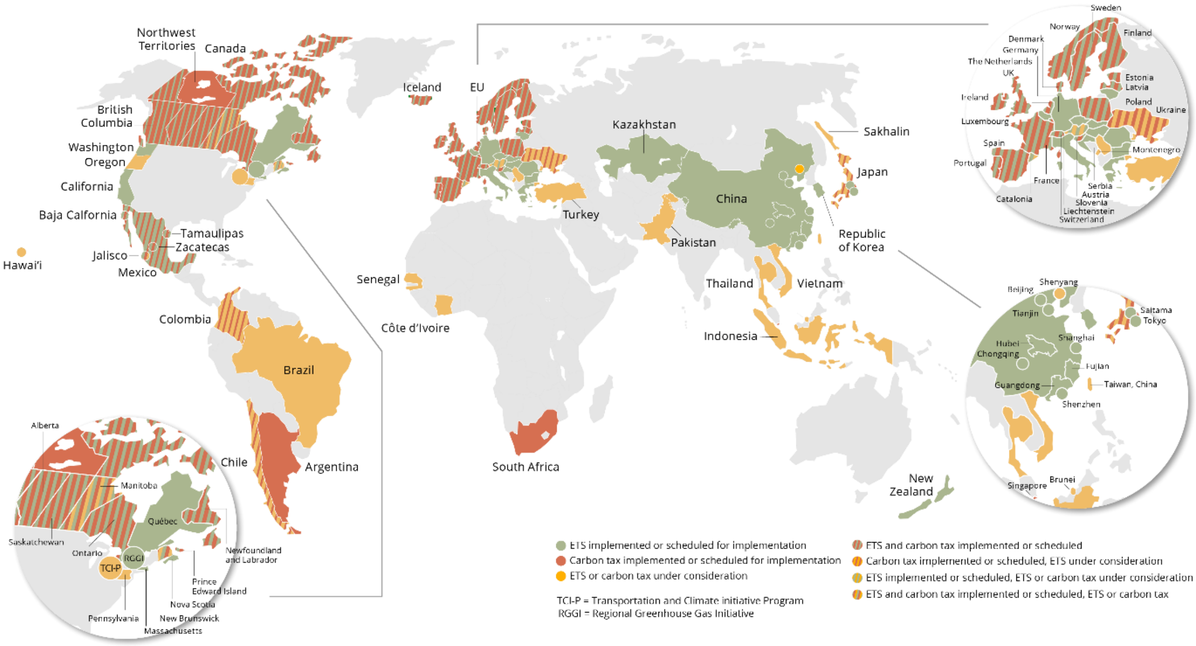

Fig. 2 – 2021 Map of carbon taxes and emissions trading[2)]

2.1 European Green Deal and EU-ETS

In the EU, the EU-ETS (Emission Trading Schedule, directive 2003/87/EC) was launched in 2005 as a result of the 1997 Kyoto protocol in which 37 industrialized countries agreed upon legally binding emission reduction targets. The EU-ETS can be classified in 4 phases:

- Phase 1 (2005-2007): Pilot of 'learning by doing'.
- Phase 2 (2008-2012): 6.5% lower cap than 2005
- Phase 3 (2013-2020): 20% lower emissions relative to 1990 by 2020
- Phase 4 (2021-2030): 55% lower emissions relative to 1990 by 2030

Originally phase 4 had a 40% lower emission target relative to 1990, under the European Green Deal this target was revised to 55% in 2020. The EU-ETS covers around 40% of the EU GHG emission, by limiting emissions from around 10,000 large installations in the power sector, manufacturing industry and airlines operating between EU airports. It operates in all EU countries plus Iceland, Liechtenstein and Norway[3)]. In July 2020 the EU presented a proposal to increase the number of installations that will fall under the EU-ETS regulations, however, as this is still in proposal phase, this data has not been included in this paper.

2.2 Measurement uncertainties per tier system

Allowed measurement uncertainties are defined in Implementing Regulation (EU) 2018/2066 of 19 December 2018, also referred to as the MRR (monitoring and reporting regulations). Per paragraph 49/4, the highest tier is to be used for determining the quantity of CO_2 transferred from one installation to another.

	Tier 1	Tier 2	Tier 3	Tier 4
CO_2 emission sources	± 10 %	± 7,5 %	± 5 %	± 2,5 %
N_2O emission sources	± 10 %	± 7,5 %	± 5 %	N.A.
CO_2 transfer	± 10 %	± 7,5 %	± 5 %	± 2,5 %

Fig. 3 – Allowed measurement uncertainties per Implementing Regulation (EU) 2018/2066 annex VIII[3)]

With regards to metrological requirements, Implementing Regulation 2018/2066 refers to national metrology regulations and to the Measurement Instruments Directive, e.g. in paragraph 18/3c: "where the specific measuring task does not fall under national legal metrological control, the substitution of measuring instruments with instruments complying with relevant requirements of legal metrological control of the Member State in similar applications, or to measuring instruments meeting national rules adopted pursuant to Directive 2014/31/EU of the European Parliament and of the Council or Directive 2014/32/EU"

2.3 OIML and MID

Looking into the OIML and MID requirements a distinction must be made between CO_2 in liquid and (supercritical) gas phase. In liquid phase both OIML R117 and MI-005 specify CO_2 measurement as a class 1,5 measurement, which means a maximum permissible error of the flow measurement system of 1,5% and 1% for the flow meter.

In gas or supercritical (gas) conditions, MI-002 is not applicable as the standard is limited to fuel gasses. OIML R137 does not have this restriction, hence could be applied for CO_2 measurement. In OIML R137 no specific reference is made to CO_2 measurement, hence the normal accuracy classification applies.

3 CO_2 PHASE DIAGRAM AND TWO-PHASE FLOW DUE TO IMPURITIES

3.1 CO_2 phase diagram and density

Under typical process conditions pure CO_2 can be found in the gas, liquid and supercritical phase. Looking at the CO_2 phase and density diagram, very large density variations can be seen when shifting between gas and liquid and between gas and supercritical close to the critical point.

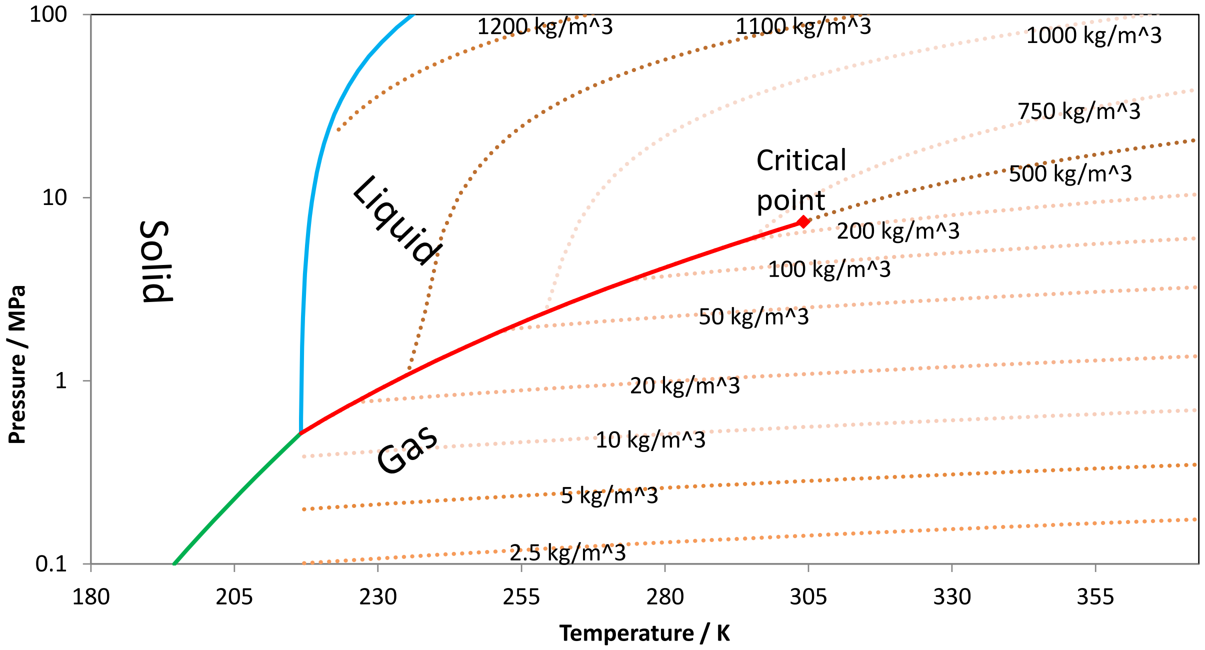

Fig. 4 – Phase diagram of pure CO_2[4)]

3.2 Comparison between CO_2 and natural gas phase diagram

While supercritical is sometimes considered an 'exclusive' feature of some specific gasses, a fair number of gasses are in supercritical phases under typical operating conditions. Pure methane for example is in supercritical phase when above -83 °C and 46 bara. With process temperatures usually far higher than -83 °C, the area with large density variations is usually avoided, hence the fact that the gas is in supercritical phase is usually not of concern.

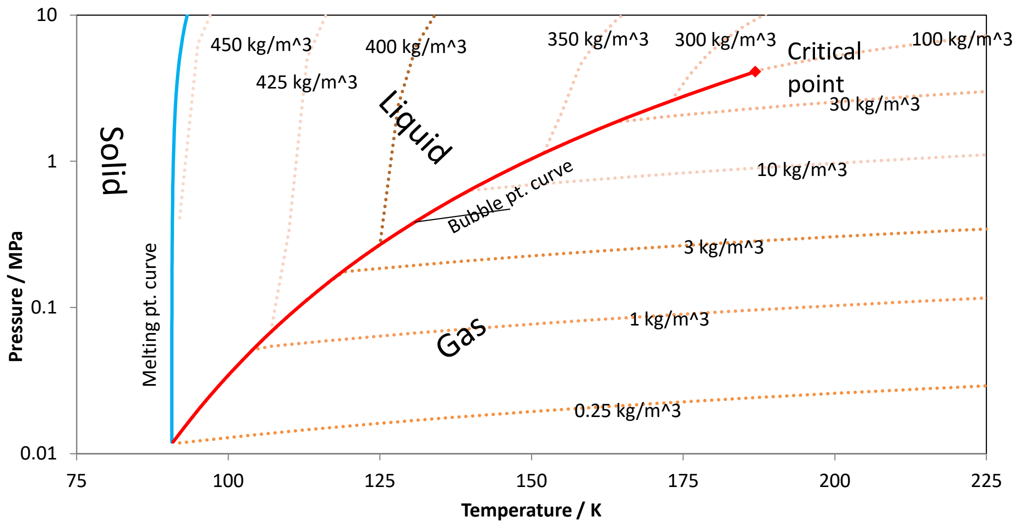

Fig. 5 – Phase diagram of methane[4)]

3.3 Two phase flow due to impurities

Besides the density jump when shifting from gaseous to liquid phase and the large density variations around the critical point of pure CO_2, there is another aspect to consider. Depending on the CO_2 capture process there could be impurities in the CO_2 that cause a two-phase flow where the composition of each phase will be different. Further details concerning capture processes can be found in for example [5].

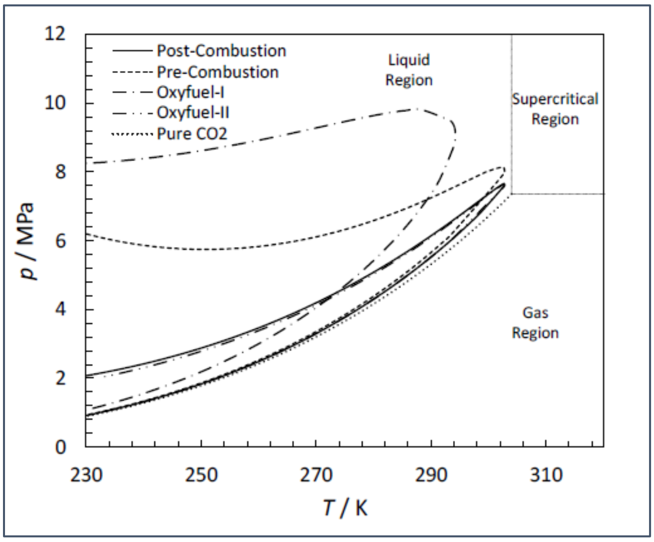

Fig. 6 – Phase enveloped of oxyfuel, post- and pre-combustion gasmixtures and pure CO_2[5]

4 TECHNICAL CHALLENGES FOR FLOWMETERS

In the past couple of years, at least two studies[9, 10] have been independently conducted on flow metering technologies with potential for application for fiscal metering for CCS. The studies span Coriolis flowmeters, differential pressure devices, i.e., orifice plates and venturi meters, ultrasonic meters, and turbine meters. From all the benchmarked technologies, turbine meters show the tightest window of operation. This responds to the dependence of the rotational speed on the fluid properties as well as the need to convert from volumetric to mass flow, which for turbine meters depends not only on the fluid density but also on the flow profile, i.e., Reynolds number and viscosity. Hence, in the following subsection, only Coriolis, ultrasonic and differential pressure flowmeters are discussed.

4.1 Challenges for Coriolis meters

In principle Coriolis meters are well suited to CCS applications by virtue of their direct mass measurement. However, there are still technical challenges that should be considered. Papers discussing the use of Coriolis meters in CCS applications mainly focus on the liquid phase performance. It was shown in[5] that the addition of impurities has minimal impact on liquid measurement accuracy but as discussed above (3.3) there could be a two-phase flow.

Hemp and Kutin[12] showed that two phase flow presents difficulties for Coriolis meters because the compressibility and buoyancy of the entrained gas bubbles within the liquid have an impact on the way the liquid moves in the vibrating tube leading to the detected forces being inconsistent with the actual mass in the tubes resulting in errors in both mass and density measurement. Attempts have been made to apply corrections using error modelling or neural networks[13] but these have not fully solved the problem. For CCS applications, the lack of larger scale test rigs limits the availability of data needed to train neural networks.

The alternative solution is to design the metering system to ensure that the flow through the meter is single phase – but this can lead to the use of costly phase separators or degassing solutions.

Coriolis meters are also suitable for the measurement of gaseous CO_2. However, again the compressibility effect also affects the measurement, though it is possible to apply a relatively simple correction based on the speed of sound of the gas. Care must also be taken when sizing Coriolis meters for gas measurement to ensure that mass flow rate is sufficient to avoid the growing error curve that mass flow meters exhibit at low flow rates due to zero stability – especially below 5% of the nominal flow rate that the meter is specified for.

4.2 Challenges for ultrasonic meters

The challenge in measuring CO_2 is found in the molecular thermal relaxation properties of CO_2. In a simplified approach this can be explained as energy being absorbed inside the C=O bonding of the CO_2 molecule. While molecular thermal relaxation is not unique for CO2, the inconvenience is that acoustic attenuation peaks in the frequency range typical for ultrasonic flowmeter.

The figure below shows attenuation due to molecular thermal relaxation under atmospheric conditions having a peak around 30 kHz. When pressure increases, the curve shifts to higher frequencies, pushing it in the operational range of mainly ultrasonic gas flowmeters. Where in the past there have been several cases where molecular thermal relaxation caused issues with ultrasonic flowmeters in high CO_2 content applications, the phenomena is better understood today, and ultrasonic transducers are selected that avoid the attenuation peak for gaseous application. For liquids, the relaxation frequency is normally far above the acoustic frequency, and hence typically the attenuation increases with the frequency squared.

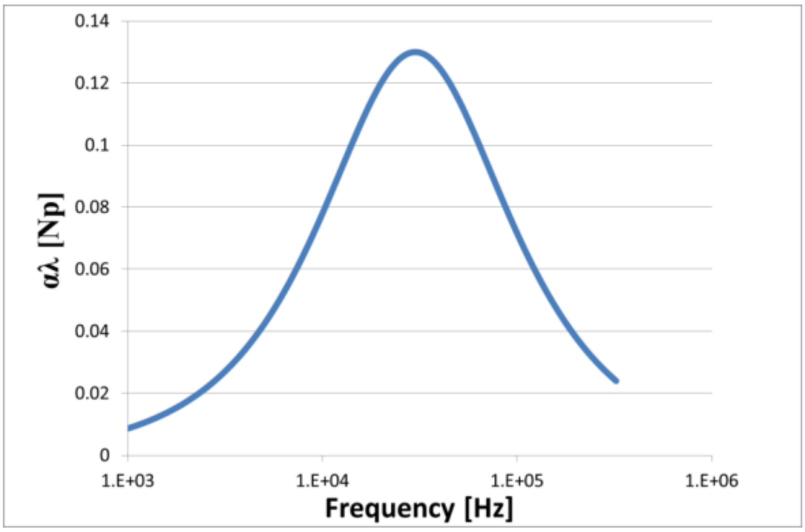

Fig. 7 – Absorption coefficient per wavelength (αλ) due to molecular thermal relaxation of CO_2 expressed in Neper at atmospheric conditions[6)]

Just like other metering principles, the second challenge lies in calibration of ultrasonic meters as no large-scale commercial flow calibration facility for CO_2 is available (see e.g. the ZEP report of 2020[11)]). For ultrasonic meters, this can in principle be covered with a Reynolds based calibration where water or natural gas is used to achieve similar Reynolds numbers as the actual application on CO_2.

Using natural gas to achieve similar Reynolds numbers as in gaseous CO_2 applications is relatively straightforward. As the kinematic viscosity of CO_2 is about 2,5 times higher than that of natural gas under similar conditions, the natural gas calibration can be conducted at a 2,5 times higher pressure or a 2,5 times higher flow velocity. Or a combination of both, depending on the possibilities of the calibration facility and maximum pressure and flowrate of the meter. For compensation of meter body expansion due to different temperature and pressure a standard equation can be used, for example those in ISO 17089.

Using water to calibrate meters that will be used on liquid CO_2 can be done according to the same principle, however the 7 times lower kinematic viscosity of liquid CO_2 means that flow calibration needs to be done at 7 times higher water flow velocities. For lower liquid CO_2 flow velocities this is feasible, however at higher liquid CO_2 flow velocities, this means the 7 times higher water flow velocities might exceed the maximum flowrate of the meter. In this case an extrapolation of the Reynolds curve will be required, like in LNG applications.

4.3 Challenges for Differential Pressure meters

Differential pressure (DP) flowmeters introduce a restriction in the pipe that induces a pressure drop across the flowmeter body. The induced pressure drop, which is correlated to the flow through the constriction, challenges the use of DP meters in certain CO_2 transport processes, particularly shipping, where operation is close to the liquid-vapor saturation line.

Orifice plates, in particular, have had a long track record of metering CO_2 in EOR applications in the US, and have been used in the demonstration project In Salah CCS, Algeria, and in the pilot capture plant of Vattenfall AB in Germany. Little to no information on accuracy is reported from these applications, with the few figures available from secondary sources lacking traceability to a relevant primary reference[7)].

Although attractive due to their inherent simplicity, extensive use, and, in principle, high accuracy at stable conditions; challenges are expected to arise when conditions deviate from calibration. Hence, the inflexibility of this technology regarding the fluid flow rate and properties is a major challenge. As discussed before, CO_2 properties have a rather high sensitivity to temperature, pressure, and small amounts of impurities at relevant conditions, yielding a degradation of the accuracy of Dp flow measurement systems under operating conditions that vary.

Further, DP measurements depend both on density and viscosity. Viscosity uncertainty is rather high even for pure CO_2 in the most recent reference model at 4% in the liquid state and 10% or above around the critical point[8)]. For mixtures, the situation is much worse as there are virtually no data.

Other limitations of orifice plates are the low turndown ratio and the strict installation requirements to ensure single-phase operation and fully developed flow. Other challenges for calibration of DP sensors are related to their capacity to measure very low full scale (FS) pressures, hence a small change in ambient temperature can amount to a noticeable change in the pressure reading. This change in temperature often equates to instabilities in both the sensor being tested and the calibration standard.

4.4 Challenges on calibration and validation

Previous work[9)] on the design of a fiscal metering calibration facility for CCS discusses possible solutions for primary references of liquid CO_2 streams. The solutions include the diversion of flow to a closed container or the use of commercial small volume provers. The authors provide an overview of the challenges and uncertainties of both configurations, which include the need for accurate back pressure control at the inlet of the container, advanced custom-made components, possibility of dry ice formation, avoidance of fast boil-off and subsequent temperature drop, control of the fast dynamics of the system's temperature, and the lack of knowledge of repeatability and accuracy of commercial volume provers for compressible liquids like CO_2.

5 DESIGN OF A METERING SYSTEMS

With CCS projects moving forward, KROHNE has been evaluating possible CO_2 metering system designs. Based on a typical application, liquid CO_2 ship loading with a nominal flow rate of 1000 m^3/h, -30 °C and 10 bar(a), a blueprint for both Coriolis and ultrasonic metering systems have been worked out.

Design basis for both options is like that of a typical metering skid for liquid hydrocarbons. Both the Coriolis and the ultrasonic systems have been designed in a master-duty Z-configuration, with either 2x 10" ALTOSONIC 5 ultrasonic flowmeters or 4x 8" OPTIMASS 6400 Coriolis flowmeters. All valves are double-block-and-bleed type to guarantee leak tightness and the full pipework is insulated. The system is equipped with an on-line analyzer and automatic sampling systems for offline analysis.

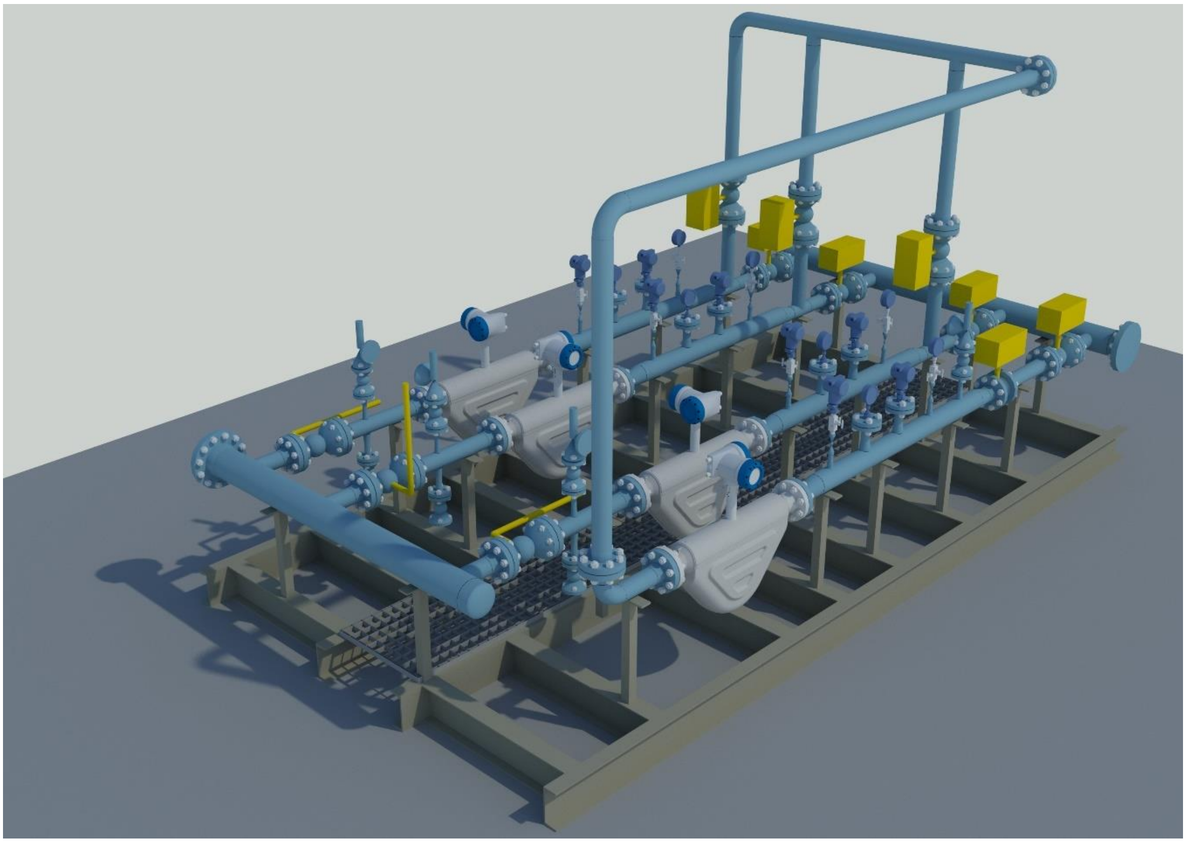

Fig. 8 – Example of a master duty Z-configuration skid mounted Coriolis metering system

Specific challenges for a CO_2 metering system and pending questions include:

- 3rd party uncertainty statement about using water calibration on CO_2 application.
- Evaluate uncertainty due to body expansion correction because of temperature differences
- Get clear understanding about OIML/MID accuracy class requirements and possibilities (e.g., is class 1,5 sufficient or is lower class requested?).
- Are compressibility and density calculations covered by existing OIML/MID approvals or is expansion of approval required?
- In case of batch operation, how to deal with degassing during standstill and during start-up cooling phase?

6 SUMMARY

In this paper we give an introduction into CO_2 trading and regulatory requirements. Specifically, we investigate required measurement uncertainties and Custody Transfer requirements for CO_2 in both liquid and gaseous phase. Based on phase diagrams and density plots we explain the specific challenges in measuring CO_2.

For Coriolis, ultrasonic and DP flowmeters a detailed review of their possibilities to measure CO_2 is done, including a section on calibration and validation. The papers ends with a possible design for a Custody Transfer metering systems for liquid CO_2 and an overview of open questions that need further clarification.

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