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Selection and Applicability of Carbon Dioxide Flow Meters in CCUS Projects

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ABSTRACT
Under global carbon neutrality strategies, the commercial application of CCUS technology demands high accuracy in carbon dioxide measurement. Since fluids transported and injected are typically in a supercritical state, drastic changes in physical properties render conventional methods incapable of meeting precision requirements. This paper analyzes the interference mechanisms of phase transitions from the fundamentals of fluid mechanics, identifying causes of deviation under impurity and extreme operating conditions. Based on technical bottlenecks, it establishes a logic for selecting equipment by operating condition zones and proposes solutions for online dynamic component compensation and hardware upgrades. This paper primarily provides theoretical support and engineering practice paradigms for flow monitoring across the entire CCUS value chain, establishing a highly reliable measurement system.

KEYWORDS
CCUS; Carbon dioxide measurement; Supercritical fluid; Phase transition; Dynamic compensation

1 Introduction

With the accelerating transformation of the global energy structure, the Carbon Capture, Utilization, and Storage (CCUS) industry chain has emerged as a critical technological pathway for achieving greenhouse gas emissions reduction. Unlike conventional oil and gas resources, captured carbon dioxide typically requires compression, liquefaction, or supercritical processing to enable efficient pipeline transportation and geological storage. This process spans a wide range of temperatures and pressures, causing the measured fluid to transition between gaseous, liquid, and supercritical states repeatedly. The nonlinear changes in fluid thermodynamic properties render traditional flow measurement instruments—calibrated based on ideal gas assumptions or single liquid phases—ineffective. In the supercritical state, even minor temperature or pressure disturbances can cause dramatic oscillations in density and sound velocity, directly impacting the repeatability and stability of flowmeter measurements. In current engineering practice, measurement data deviations directly undermine the legal foundations for fair settlement in carbon trading markets and carbon tax assessments. They also affect pipeline integrity management and compliance verification of total geological storage volumes. Addressing the nonlinear abrupt changes in fluid density and sound velocity across critical regions hinges on understanding the strong coupling between fluid properties and instrument response characteristics within complex thermodynamic environments. This requires establishing a systematic measurement methodology that spans all phase states and adapts to extreme operating conditions.

2 Fundamental Theoretical Analysis of CO_2 Measurement in CCUS

2.1 Physical Characterization of CO_2 Phase Transition

As a single-component fluid, CO_2 exhibits highly sensitive thermodynamic properties near its critical point. During CCUS transportation, the fluid is often maintained in the supercritical or dense-phase region, where its density approaches that of a liquid. At the same time, its viscosity resembles that of a gas. According to the Span-Wagner equation of state, when operating parameters approach the critical point, the isothermal compression coefficient undergoes an order-of-magnitude abrupt change. This causes the fluid density to react extremely violently to variations in temperature and pressure. The nonlinear nature of these physical property changes demands that flow meters possess a wide dynamic measurement range and high frequency response speed to capture transient flow variations.Additionally, the speed of sound varies significantly across different phases, with a substantial difference between gas and liquid phases. During transcritical processes, regions of minimal sound velocity exist, posing a severe challenge for instruments relying on acoustic principles for measurement [1]. Accurately characterizing the variation patterns of density, viscosity, and sound velocity across each phase constitutes the fundamental physics for achieving high-precision flow measurement.

2.2 Technical Principles of Mainstream Flow Measurement

Currently, Coriolis mass flowmeters, ultrasonic flowmeters, and differential pressure flowmeters represent the

mainstream technical approaches for CCUS measurement in industrial applications. Coriolis flowmeters directly measure mass flow by generating the Coriolis force effect within vibrating tubes. Their primary advantage is insensitivity to fluid rheology, theoretically enabling direct measurement of both gas and liquid phases. However, during high-pressure dense-phase transport, pressure compensation is required to account for changes in the rigidity of the vibrating tubes. Ultrasonic flowmeters calculate velocity by measuring the time difference between ultrasonic pulses traveling upstream and downstream. Their non-contact measurement eliminates pressure loss but demands high stability in fluid sound velocity and uniformity in flow field distribution. Differential pressure flowmeters calculate flow based on the Bernoulli equation using the pressure difference across a throttling element. While technically mature, they require precise fluid density parameters. Under non-ideal gas conditions, the selection of the equation of state directly impacts the calculation accuracy of differential pressure flowmeters. Flowmeters based on different principles exhibit vastly different dynamic response characteristics when handling unsteady flows and phase-changing fluids.

2.3 Evaluation Index System for Measurement Accuracy

Establishing a scientific measurement evaluation system is crucial for ensuring data reliability. For CCUS projects, evaluation metrics should not rely solely on accuracy grades but must encompass repeatability, linearity, zero stability, environmental adaptability, and other factors. Trade-point metering systems require high accuracy, typically benchmarked against Class 0.1 or 0.2 standards, primarily assessing flowmeter linearity across the full range and long-term drift performance. For process control points, evaluation focuses on instrument repeatability and response time to ensure rapid feedback to process fluctuations. Given the highly compressible nature of carbon dioxide fluids, measurement errors in pressure and temperature are amplified through density calculation formulas. Therefore, the evaluation system must incorporate a comprehensive uncertainty assessment of the temperature-pressure compensation system [2]. Additionally, the unique characteristics of supercritical fluids must be considered, with interference resistance in the phase transition critical region serving as an evaluation metric. Standards for metrological instrument acceptance and graded calibration should be established based on different process segments.

3 Practical Challenges in Flowmeter Selection for Complex Conditions

3.1 Measurement Deviations Caused by Supercritical Phase Transitions

During supercritical carbon dioxide transportation, pressure drops along pipelines or ambient temperature fluctuations can readily induce localized phase transitions, resulting in gas-liquid two-phase flow patterns. For Coriolis mass flowmeters, the non-uniform flow causes a sharp increase in measuring tube damping. This fluctuation in drive gain exceeds the transmitter's adjustment range, leading to tube oscillation cessation or distorted readings. Particularly when the fluid exhibits bubble flow or plug flow, the asymmetric impact of bubbles on the tube wall generates false Coriolis forces. This results in mass flow readings that deviate significantly from actual values. For ultrasonic flowmeters, the gas-liquid interface generated by phase change causes severe scattering and attenuation of ultrasonic signals, reducing the signal-to-noise ratio and even resulting in signal loss. Conventional signal processing algorithms struggle to distinguish between fluid noise and valid signals, leading to violent fluctuations in instantaneous flow calculations. Since phase transition-induced measurement failures are often sudden and random, conventional single-phase calibration data cannot cover such complex operating conditions, casting doubt on the reliability of on-site measurement data.

3.2 Measurement Interference Caused by Multi-Component Impurities

Industrially captured carbon dioxide is not a pure substance; it often contains impurities such as nitrogen, oxygen, water vapor, hydrogen sulfide, and light hydrocarbons. These impurities not only alter the fluid's critical parameters but also cause significant deviations in the state equation calculation model. Even small amounts of hydrogen or nitrogen can markedly lower the critical temperature of the mixed fluid. This causes the fluid, which was originally transported in the liquid phase, to transform into a two-phase gas-liquid state or a supercritical state under the same temperature and pressure conditions, directly disrupting the flowmeter's preset operating reference [3]. In differential pressure flowmeters, variations in impurity components directly alter the fluid's isentropic exponent and compressibility factor. Using pure-component physical data for flow calculation introduces systematic errors. Furthermore, water-containing impurities readily form hydrate ice plugs under low-temperature, high-pressure conditions. These deposits adhere to orifice plate edges or flowmeter walls, altering flow area and distribution patterns, thereby distorting differential pressure signals. In acoustic measurement, sound velocity drift caused by fluctuating impurity concentrations, if not corrected in real time, directly translates into flow velocity measurement errors. These errors accumulate nonlinearly with impurity content, leading to exponential amplification of measurement inaccuracies.

3.3 Structural Degradation in Ultra-High Pressure Environments

Injection pressures during CCUS sequestration often reach tens of megapascals. Prolonged exposure to pulsating high-pressure conditions inflicts irreversible physical damage on flowmeter structures. Coriolis flowmeter measuring tubes undergo wall hardening under high static pressure, causing meter coefficient drift. High-pressure stresses also accelerate microcrack propagation in measuring tubes, posing fatigue fracture risks. For insertion-type ultrasonic flowmeters, high-pressure fluid impacts can easily cause probe loosening or seal failure, potentially leading to dangerous probe ejection. High-pressure environments accelerate fluid erosion of throttling elements, blunting orifice plate edges, or altering venturi throat dimensions, permanently reducing measurement accuracy. During rapid pressure relief, carbon dioxide gas permeating into rubber seals or lining materials undergoes explosive volume expansion. This causes explosive decompression failure, leading to lining delamination or seal ring fragmentation, rendering the flowmeter completely inoperable. The pressure resistance and fatigue endurance of the hardware structure thus become the physical bottleneck affecting the long-term stable operation of the flowmeter.

4 Optimization Pathways for Flow Meter Suitability in CCUS Projects

4.1 Selection Matching Strategy Covering Multiphase Conditions

The first step in the flow meter selection strategy involves establishing a selection matrix by coupling process flow diagrams with phase diagrams. In the low-pressure gas phase zone at the capture end, thermal gas mass flow meters or ultrasonic gas flow meters should be prioritized to accommodate low flow rates and low-density measurement environments[4]. In high-pressure dense-phase or supercritical zones during pipeline transportation and injection, high-pressure Coriolis mass flowmeters should be the preferred choice due to their direct mass measurement capability. However, their operating pressure rating must be strictly limited, and corresponding pressure stiffness correction factors must be configured. For transition pipe sections exhibiting gas-liquid two-phase flow, transmitters capable of handling multiphase flow must be employed. These should monitor drive gain and density fluctuations, identify flow pattern changes, and activate two-phase flow compensation algorithms. Large-diameter transmission lines employ multi-channel ultrasonic flowmeters paired with high-precision temperature/pressure transmitters to achieve low-pressure-loss measurement. The selection process must abandon the mindset of relying on a single universal instrument, instead adopting a systematic approach featuring segmented matching and redundant configurations. This ensures each flowmeter operates within its optimal physical characteristic range.

4.2 Dynamic Correction Scheme for Impurity Compensation Algorithms

To eliminate measurement errors caused by component fluctuations, a dynamic compensation system integrating real-time component monitoring must be established. The core of this approach involves incorporating online gas chromatographs or laser gas analyzers to continuously capture molar fractions of impurity components within the fluid, transmitting this data to the flow computer. The flow computer must incorporate high-precision state equation models suitable for mixtures, such as GERG-2008 or EOS-CG, replacing traditional lookup tables or ideal gas formulas. Based on measured component, temperature, and pressure data, the system performs real-time iterative calculations for the compressibility factor, density, viscosity, and isentropic exponent of the mixed fluid, dynamically correcting the flow meter's raw output signal. For ultrasonic flowmeters, diagnostic logic based on sound velocity verification can be established. When the deviation between measured and calculated sound velocity exceeds a threshold, an alarm is automatically triggered, and backup correction factors are invoked, thereby mitigating blind spots in physical property calculations caused by impurities. This closed-loop correction mechanism, integrating hardware and software, transforms passive table lookup into proactive real-time computation, fundamentally resolving drift issues in physical parameters caused by impurities.

4.3 Pressure-Resistant and Corrosion-Resistant Material Improvements for Critical Components

For CCUS extreme operating conditions, material upgrades and structural optimization of flowmeter core components form the physical foundation for enhancing applicability. Sensor wetted parts should utilize Hastelloy, super duplex stainless steel, or titanium alloys to improve resistance against chloride ion corrosion and hydrogen embrittlement, particularly for non-pure CO_2 fluids containing water or sulfur. Sealing structures must completely abandon traditional rubber materials, instead employing PTFE-graphite-filled or metal-graphite-wrapped gaskets. Special explosion-proof pressure relief channels should be incorporated to eliminate risks of explosive depressurization damage [5]. Coriolis flowmeter measuring tubes require cryogenic treatment or self-strengthening processes to eliminate residual stresses,

enhance yield strength and fatigue limit, enabling them to withstand pulsating impacts from high-pressure fluids. Simultaneously, a secondary containment shell must be added externally to the sensor. Even if the core element ruptures, high-pressure fluid will remain confined within the instrument, preventing leakage. By deeply integrating materials science with mechanical design, an intrinsically safe hardware defense line for flow measurement is established.

5 Conclusion

Flow measurement in CCUS projects transcends engineering challenges, encompassing complex fluid physics and materials science. The phase sensitivity of carbon dioxide in the supercritical region, the diversity of impurity components, and the destructive nature of high-pressure conditions collectively impose multiple constraints on precise flowmeter selection. High-precision measurement cannot rely solely on a single instrument. An integrated solution must be developed that combines operating condition zoning for selection, dynamic component compensation, and material reinforcement. This requires deeply coupling fluid physical properties with measurement principles, using real-time state equation corrections to overcome existing bottlenecks. This approach provides crucial solutions for trade settlement and process control challenges, serving as an indispensable pathway for standardizing carbon capture technology development.

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