

Research Progress of Supercritical / Dense Phase CO₂ Flow Metering Technology

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Abstract: Carbon Capture, Utilization, and Storage (CCUS) technology plays a vital role in achieving the "carbon neutrality" strategic goal. However, one of the significant challenges in realizing this objective is the precise measurement of CO₂ flow rates. Based on a literature review of current applications of flow measurement in CCUS processes at home and abroad, this study analyzes the influencing factors of flow meter selection and installation, as well as the impacts of different types and concentrations of impurities in CO₂ streams on measurement accuracy. It identifies the primary reasons for inaccuracies in CO₂ flow measurement, namely the unique phase behavior of impure CO₂ and nonlinear variations in density. The research summarizes practical engineering applications and existing studies on CO₂ flow measurement, proposing measures such as optimized flow meter selection, installation positioning strategies, and density correction methods. These findings aim to provide references for precise CO₂ flow measurement in CCUS projects and the promotion of CCUS technology. Further development of CCUS technology necessitates deeper research on accurate CO₂ flow measurement. Building on previous engineering experiences and scholarly investigations into precise CO₂ mass flow measurement, this paper suggests improvements and recommends future directions, including computational fluid dynamics (CFD) numerical simulations tailored to real-world operational conditions. Such advancements could lead to more effective solutions for accurate CO₂ mass flow measurement in practical applications.

Keywords: CCUS, CO₂ pipeline transportation, CO₂ flow measurement.

1. Introduction

China announced to the world at the UN General Assembly that it would achieve a carbon peak by 2030 and achieve a carbon neutral by 2060 [1]. CCUS technology is one of the indispensable key technologies to be carbon neutral. In February 2023, The State Council issued the Outline for Building a Strong Quality Country, which clearly proposed to "establish and improve the carbon peak and carbon neutral standard measurement system, and promote the establishment of international mutual recognition of carbon measurement base standards, carbon monitoring and effect evaluation mechanism.

Therefore, it is necessary to accelerate the layout of CCUS measurement standards, and promote the standard formulation with scientific research, demonstration and promotion. Strengthen the key and core technologies of measurement, and promote the intelligent, digital and networked of measuring instruments. In all aspects of CCUS technology, accurate CO₂ metering is critical, including flow measurement in the carbon capture phase, flow monitoring of CO₂ pipelines, and of reasonable gas distribution in the CO₂ flooding (CO₂-EOR) injection system. Currently, CCUS uses multiple flow metering techniques, such as Coriolis mass flowmeter and multiple volume flowmeters (such as hole plate flowmeter, turbine flowmeter and ultrasonic flowmeter)[2-5]. Since CO₂ emissions are traded in quality units in carbon credit plans, it is particularly important to accurately measure the mass flow of CO₂. However, in practical engineering applications, the high cost of Coriolis mass flowmeters and their limitations in large diameter applications pose significant challenges to achieving the 1.5% measurement uncertainty required by policy guidelines. Therefore, the accurate measurement of the whole process

CO₂ is the basis and guarantee to achieve the policy objectives.

In the current CCUS technology process, the problem of imprecise CO₂ measurement is still common. On the one hand, under the actual operating conditions, because the critical temperature of CO₂ (the critical point of pure CO₂: $t_c=31.4^{\circ}\text{C}$, $p_c=7.38\text{MPa}$, the critical point of the impurity CO₂ is offset) is close to the ambient temperature, and the temperature pressure of CO₂ will change during the flow process. For example, in the oil field, the measurement deviation reaches 20%. The reason for this deviation rate by Xiong Gangqiang et al. [6] analysis is the formation of tiny bubbles after the saturated carbon dioxide is affected by the high temperature of the external environment which affects the measurement accuracy. On the other hand, the composition and content of different impurities will greatly change the physical property parameters of CO₂, and the density of impurity CO₂ shows typical nonlinear characteristics with temperature and pressure, which also brings difficulties to accurately measure the mass flow of CO₂. Through the analysis of CO₂ physical properties, Chen Bing et al. [7] concluded that the impurity component will change the critical point of CO₂, so that the density of impurity CO₂ in the transmission process is more easily affected by the temperature and pressure change, resulting in two-phase flow and other situations, resulting in inaccurate measurement.

At present, there is a lack of review literature on impurity CO₂ flow measurement based on CCUS technology. This paper investigates the relevant literature of CO₂ flow measurement at home and abroad, combined with domestic and foreign engineering.

2. Advances in CO₂ Flow Measurement Technology

At present, the purpose of impurity CO₂ flow measurement is mainly used for transportation monitoring and internal company records. With the development of the carbon trading market, it will also be used for the measurement link in carbon trading [8].

2.1. Measuring principle and characteristics

CO₂ The measurement principle is currently divided into two aspects, one based on the volume flow, on the other based on the mass flow.

2.1.1. Volume measurement

Volume measurement is a method of measuring a certain volume, which is widely used in oil trade. The principle based on volume is to correct the density of temperature, pressure and impurity components. This density modification method needs to use the equation of state. As the GERG-2008 equation of state claims that the error is less than 1% [9]. in the typical pipe temperature and pressure range. Common volume flowmeter, turbine flowmeter, orifice plate flowmeter, vortex flowmeter, ultrasonic flowmeter, etc.

1. Turbine flowmeter is a velocity-type measuring instrument characterized by high measurement accuracy, good repeatability, small size, and light weight, which has been widely applied. The principle is that when the fluid passes through the flowmeter, the volume flow rate of the fluid is measured by counting the number of revolutions or the rotational speed of the impeller [10-11]. It is suitable for high-pressure environments such as petrochemicals, natural gas transmission, CO₂, etc.

2. Orifice plate flowmeter has years of experience in measuring CO₂. Its measurement principle is based on the fact that when a fluid flows through a throttling device, the sudden decrease in the cross-sectional area of the pipe causes a pressure difference before and after the device. This pressure difference has a certain functional relationship with the flow rate, thus allowing the flow rate to be measured through this pressure difference [12]. As a traditional differential pressure flow measurement instrument, the orifice plate flowmeter has the advantages of low cost and simple structure. However, its disadvantages are also significant. The orifice plate causes an increase in fluid kinetic energy due to the contraction of the flow path, resulting in a significant decrease in static pressure and the formation of large irreversible pressure loss. This pressure loss is particularly problematic for CO₂ fluid near the critical point, where phase transitions occur.

3. Vortex flowmeter is widely used in industrial process measurement. They are a type of fluid vibration flowmeter based on the Karman vortex street principle. By measuring the frequency of the vortices generated by the fluid, which is proportional to the flow velocity of the fluid, the flow velocity can be determined, and thus the fluid flow rate can be calculated. Moreover, vortex flow meters have unique advantages in the field of oil and gas drilling [13-15]. However, when the fluid velocity is below 0.5m/s (liquids) or 5m/s (gases), it is difficult to form a stable vortex street, leading to a decrease in accuracy or even the inability to

measure.

4. Ultrasonic flowmeter belongs to the category of differential velocity flowmeters, which are based on the impact of the fluid flow process on the internal acoustic signals and obtain flow information by examining the changes in these acoustic signals. The variation in propagation speed is related to the motion speed of the medium. Existing ultrasonic measurement methods can be divided into types such as the propagation velocity difference method, Doppler method, beam shift method, correlation method, and noise method [16-17]. The limitations of ultrasonic flowmeters in the measurement of supercritical CO₂ mainly stem from signal absorption, phase sensitivity, and calibration challenges. For such high-demand application scenarios, it is recommended to preferentially choose other types of volumetric flowmeters.

2.1.2. Mass measurement

Mass measurement is achieved by directly measuring the mass flow rate. The Coriolis mass flowmeter is widely used due to its higher measurement accuracy compared to other types of flowmeters. The Coriolis mass flowmeter is based on the principle of Coriolis force, utilizing the fluid flow in a vibrating tube to generate a Coriolis force proportional to the mass flow rate. This force can be directly measured and used to calculate the fluid's mass flow rate, making it a direct mass flowmeter. Its advantages include the ability to directly measure the fluid's mass flow rate with high accuracy and without the need for straight pipe sections before and after the meter [18]. The Coriolis mass flowmeter is indispensable in scenarios requiring high precision, multiple parameters, and complex media. However, its cost, sensitivity to vibrations, and pipe diameter limitations (with a maximum applicable diameter of only DN150~200mm) must also be considered.

3. Current Status of CO₂ Flow Measurement Domestically and Internationally

The research of CCUS technology abroad started earlier. At present, many developed countries and regions, such as the European Union, the United States, Norway and other places, have successively carried out hundreds of CCUS projects. Therefore, it is necessary to ensure the promotion and development of CCUS technology through the whole measurement of CO₂. The following will analyze the causes of the current CO₂ flow measurement problems based on the measurement principles and the existing standards.

3.1. CO₂ Measurement Existing Standards

According to the standard SY/T 7440-2019 Design Code for CO₂ Drive Oilfield Injection and Production System issued by the National Energy Administration of China, CO₂ should be measured by unit of quality. Among them, when the oil field and external market trade handover, the measurement accuracy required is primary measurement, and the measurement accuracy required for internal oil field production is secondary and tertiary measurement, as shown in Table 1.

Table 1. General provisions of CO₂ flow measurement in the Design Code for Injection and Production System of CO₂ Drive Oil Field

Measurement accuracy level	Measurement scene	margin of error	Flow meter selection
Level I measurement	Oil field trade with external markets	±2%	A mass flow meter should be selected
Level II measurement	nternal oilfield production metering	±10%	It is appropriate to choose differential pressure flow meter or volume meter flow meter, online measurement should be used temperature pressure compensation, liquid phase can also be measured by volume unit
Level III measurement	Single-well production measurement in the oil field	±15%	

With the development of CCUS technology, it is necessary to promote its large-scale engineering application, and the supercritical or dense phase is generally selected for transportation and injection. According to the specification requirements, CO₂ flow quality unit measurement, and due to the different measurement accuracy requirements, the measurement schemes according to the specific situation are also different, the mass flow meter for CO₂ flow measurement, the second and third level of measurement, differential pressure or volume flow meter, and density measurement or calculation to obtain the mass flow. Therefore, it is necessary to investigate the actual engineering cases of CO₂ measurement at home and abroad, summarize the successful engineering experience and existing problems, analyze the

reasons and put forward improvement measures, so as to provide reference for the accurate measurement of CO₂ in each technical link of the future CCUS technology process in China.

3.2. CO₂ Application status of flowmeter engineering

For the engineering application of CO₂ flowmeter, the literature is investigated. Table 2 is the current available literature data, according to the data, the injection pipeline of the CO₂ uses turbine flowmeter and orifice plate flowmeter for CO₂. As shown in Table 2.

Table 2. Application status of CO₂ flowmeter engineering at home and abroad[19-26]

Measuring the location	flowmeter	Flow meter type	position of assembly	phase state	The deviation rate	Tube pressure/MPa	pipe diameter /mm
Timbalier Bay	orifice meter	volume	Transmission pipe entrance	supercritical state	\	9.31	152.4
Hansford Marmaton	orifice meter	volume	Transmission pipe entrance	supercritical state	\	10.69	152
Hansford Marmaton	turbine flowmeter	volume	Transmission pipeline exit	supercritical state	\	10.69	152
Yates Oil Field	Coriolis mass flowmeter	mass	Injection of wellhead	gas-liquid two-phase	5%	5.52-7.03	\
Yates Oil Field	Vortex Flowmeter	volume	Injection of wellhead	gas-liquid two-phase	\	5.52-7.03	\
Yates Oil Field	orifice meter	volume	Injection of wellhead	gas-liquid two-phase	80%	5.52-7.03	\
Yates Oil Field	DP flow meter	volume	Injection of wellhead	gas-liquid two-phase	80%	5.52-7.03	\
Shengli Oil Field	\	volume	Injection of wellhead	Full phase state	7%	\	\
Jiangsu oilfield	ultrasonic flowmeter	volume	Injection of wellhead	liquid phase	\	\	\
North Jiangsu oilfield	mass flowmeter	mass	Injection of wellhead	gaseous phase	0.45%	\	\
Daqingzijing Oilfield	\	\	\	\	20%	\	\
Dover 36 Facility	Coriolis mass flowmeter	mass	Injection of wellhead	\	\	9.65	\
Dover 36 Facility	Coriolis mass flowmeter	mass	high-pressure separator	\	\	>3.45	\
Dover 36 Facility	Vortex Flowmeter	volume	light pressure separator	\	\	<3.45	\
Saudi Aramco	Coriolis mass flowmeter	mass	Injection of wellhead	Supercritical state / dense phase	\	11.03	\

3.3. CO₂ Research status of the flowmeter

The Mountain Pipeline in the United States provides the CO₂ transportation pipeline network for multiple CCS plants. Since the network is shared between different users, accurate measurement of this delivery pipe network is considered to ensure accurate distribution between users. Part of the network uses a turbine flowmeter to measure the flow of supercritical / dense phase CO₂. Due to the potential for phase transition in pipeline transmission, the mass flow [27] is calculated indirectly by density measurement in the pipe network.

Steven [28] Using the hole plate flow meter; the equation, together with ISO-5167 standard measuring the flow rate with the differential pressure device installed in the circular section pipe filled with fluid, obtained a new flow estimation method, tested with carbon dioxide and natural gas mixture, the uncertainty is lower than the related uncertainty of the standard formula. In order to supplement the experimental data on the critical flow of supercritical CO₂, Jun [29] et al. established a new model to conduct the critical flow experiment through the hole plate. From the extended results, the mass flow and the prediction ability of the critical pressure are better than the previous ones.

Wang [30] uses vortex street flowmeter and uses the Peng-Robinson formula for density compensation for CO₂ measurement. At the same time, the hardware and software design is carried out, so that the vortex flowmeter can reach the lower range lower limit, broadening the range ratio of the vortex flowmeter when measuring supercritical CO₂.

Although the ultrasonic flowmeter has the advantage of contact, on the one hand, the cost of the ultrasonic flowmeter is much higher than the rest of the flowmeters; on the other hand, the high purity CO₂ will affect the accuracy of the ultrasonic flowmeter [31] due to its large acoustic attenuation, which limits the application of the ultrasonic flowmeter in CO₂.

Many scholars have focused on the accurate measurement technology of Coriolis mass flow meter applied to CO₂ flow measurement in CCUS technology. Luo [32]-33] et al. believed that the Coriolis mass flowmeter can be used in CO₂ without modification, and designed a differential pressure combined flowmeter of the Coriolis mass flowmeter as a throttle part. Through the differential pressure transmitter measured the Coriolis mass flowmeter pressure difference, and calculated the mass flow of the measured medium. The maximum error of this combined flowmeter is only-1.69%, indicating that this combined flowmeter can be used for accurate measurement of supercritical carbon dioxide. Lin [34] selected industrial scale Coriolis mass flowmeter, weighing CO₂ by high precision weighing scale, based on weight calibration, a set of CO₂ Coriolis mass flowmeter measurement system, and the measurement results of Coriolis mass flowmeter, the temperature range is 290-303K, the pressure range is 6.5-8.5MPa, and the flow rate range is 25-60kg / h. The final uncertainty was 0.11%, which indicates that the Coriolis mass flowmeter is suitable for application in CCUS engineering. Adefila[35-36] et al. used multiple groups of Coriolis mass flowmeters to measure the mass flow of pure CO₂, and took the single-phase CO₂ gas Coriolis mass flowmeter as a reference, and a mean speed tube with flow adjustment wing was installed on the horizontal experimental

device, and the measurement error was within the range of $\pm 1\%$. It is concluded that the flow obstruction decreases, thus the measurement accuracy. And further evaluated the measurement error of the sensor under wet gas conditions. It show that the measurement error can be controlled within $\pm 1.5\%$ when the liquid content is up to 20%. Wang [37] et al. proposed a gas-liquid two-phase CO₂ measurement method based on the Coriolis mass flowmeter and least squares support vector machine model. The Coriolis mass flowmeter applying this algorithm has less than $\pm 2\%$ on the horizontal pipeline and less than $\pm 1.5\%$ on the vertical pipe.

4. CO₂ Cause Analysis of Imprecise Flow Measurement

With the release of document no. 1093,2023, when the CO₂ of domestic CCUS project is more than 100,000 tons, CO₂ pipeline should be built in principle. At present, CO₂ long distance pipeline diameter is large, but the measuring precision is difficult to apply [38] (the development of Coriolis mass flowmeter with diameter of more than 150mm is still difficult [39]). At present, the accuracy of volume flowmeter is low in the existing CO₂ delivery pipeline, so the causes of volume flowmeter imprecision will be analyzed in this paper.

4.1. Analysis of causes

Timbalier Bay And in the Hansford Marmaton project, the CO₂ of the delivery pipeline is measured, in which Timbalier Bay uses the orifice plate flowmeter for CO₂ before the delivery pipeline, and the Hansford Marmaton field after the compressor station and the field uses the standard orifice flowmeter and standard turbine flowmeter for CO₂. The diameter of both pipes is greater than 150mm, and the volume flowmeter is used. Yates Oil Field The Coriolis mass flowmeter is more accurate in the gas-liquid flow in phase flow, and the measurement deviation of the hole plate flowmeter reaches 80%. Take CO₂ oil drive test as an example. Its main production process: the CO₂ separated from the natural gas is divided into two parts. One part is cooled and liquefied by the low temperature liquefaction unit and stored in the low temperature liquid CO₂ storage tank, And the storage tank will be used for tank truck transport or recycled after pipeline pressurization; the other part will be directly distributed and recycled. The main metering points include: 1. Low temperature storage tank to tank car; 2. Low temperature storage tank to injection station; 3. front of high pressure compressor; 4. High pressure single well. During the test, the measurement deviation of the highest CO₂ flow is as high as 20%, which is unacceptable for the online measurement monitoring of the project. By analyzing the reasons, it is learned that CO₂ is mainly affected by environmental temperature in the measurement process, phase change and gas-liquid flow, resulting in the measurement error [6].

According to the results of literature research, the volume flowmeter is mostly used in the transportation pipeline, and the volume flowmeter has a large error in the measurement, and the Coriolis mass flowmeter is mostly used in the injection wellhead, and the measurement error is small. Because the long-distance delivery pipe diameter is usually greater than 150mm, the current Coriolis mass flowmeter cannot be applied. Therefore, the volume flowmeter is mainly used to measure the flow rate of the supercritical / dense phase

CO₂ flow of the long transmission pipeline, according to the measurement principle and the problems in the engineering. On the one hand, the ambient temperature will affect the fluid in the actual engineering. The CO₂ density changes nonlinear with the temperature and pressure, which is prone to appear two-phase flow, which leads to a large error in the CO₂ flow measurement. On the other hand, because of the capture way (such as after combustion, combustion and oxygen rich combustion, etc.), gas source distribution (such as furnace flue gas, catalytic cracking flue gas, etc.) is also wide [40], capture CO₂ impurity type and content of different [41], and gas impurities have a great impact on physical properties, causing the CO₂ mass flow measurement, so accurate measurement method still need to explore.

4.2. Influence factors

4.2.1. Effect of the impurities on the CO₂-phase characteristics

For the current problems facing the flow measurement of

impurity CO₂, the first is the special physical properties of CO₂. The common working range of CCUS is the yellow area in the figure, and the boundaries are near the critical point. When the transmission pressure is stable above 7.37 Mpa, it is not difficult to see that the boundary temperature condition between the supercritical state and liquid CO₂ is very close to the temperature (10~40°C) in the natural environment of many parts of the world. However, due to natural environmental factors such as day and night, the actual working condition tends to cross the phase boundary, resulting in CO₂ phase change in the pipeline. However, in the actual working condition, the transmission pressure drops to a certain extent with the growth of the pipe length, which makes it difficult to maintain the pressure above 7.37MPa. This is especially true for large, long-distance pipelines, as shown in Figure Figure 1.

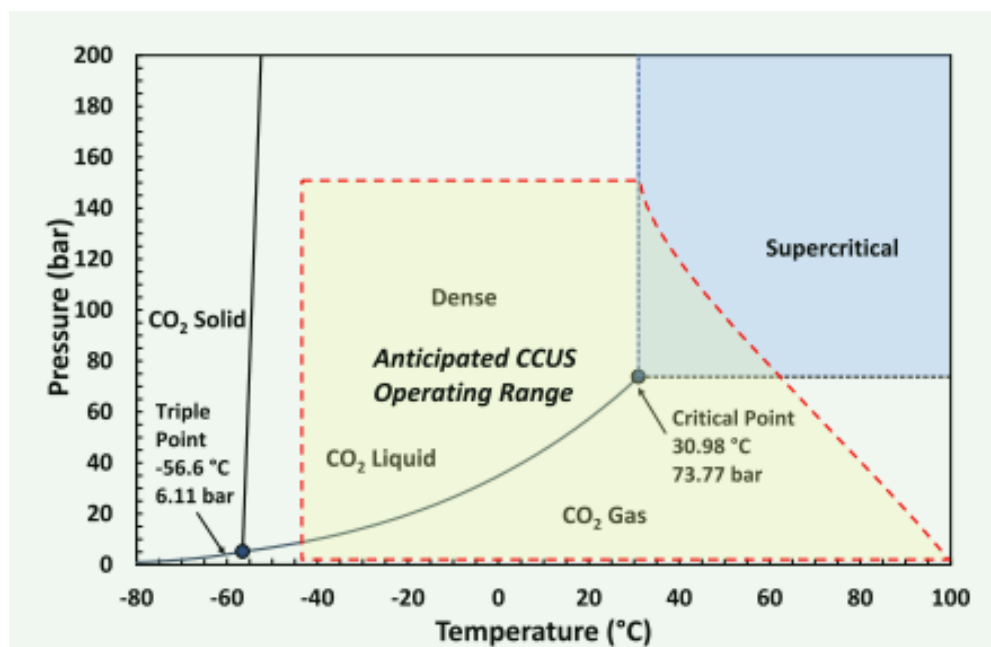


Figure 1. Pure CO₂ phase diagram (CCUS working range highlighted in yellow) [42]

Therefore, combined with the changes of temperature and pressure, it can be found that in the actual working conditions, the CO₂ in the transmission pipeline may appear two-phase flow or even three-phase flow. Whether it is liquid, gas, gas-liquid, or supercritical, it will face different measurement problems [43-45]. If the CO₂ state in the flow measurement is near the critical point, it will not only have a great impact on the accuracy of the flow measurement, but also affect the control of the whole system. Based on the influence of the special physical properties of CO₂ on its flow measurement, the impurities present in the CO₂ flow in the actual working conditions further increase the possibility of the CO₂ phase transition. Hassanpouryouzband[46] et al studied the mixture of different concentrations of CO₂ and H₂ and found that the critical point shifted significantly as the hydrogen concentration increased. H₂ affects the critical pressure, while SO₂ and N₂ [47] the critical temperature.

The type and content of impurities can cause a significant offset [42] in the phase boundary, critical point, especially in the two-phase region. Different types and contents of

impurities have different effects on CO₂ phase balance and physical property parameters. N₂ and H₂ significantly affect the phase properties of the mixture compared with the other components.

4.2.2. Effect of impurities on the change in the CO₂ density

In addition to the phase characteristics, the impurity also seriously affects the CO₂ density with temperature pressure. Wang Hongchao [48] studied the function relationship between the mixture pressure and density of CO₂ and N₂ at different temperatures, and compared it with pure CO₂, and concluded that 5% N₂ impurities had a great influence on the relationship between CO₂ density and pressure. Shu [22] studied the effect of different concentrations of N₂ on CO₂, and found that with the increase of N₂ concentration, the influence on the density gradually increased, and gave the parameter range of carbon dioxide pipeline operation for comparison. Studies is also shown that trace impurities (e. g., NO_x, SO_x, N₂, H₂S, H₂O, and CH₄) may have a significant impact on the density and compressibility of process flow

[49].

In conclusion, the presence of impurities will lead to large changes in the critical point and phase characteristics of the CO₂ fluid, and the density also changes nonlinearly with the temperature and pressure, so that it is difficult to accurately measure the volume flowmeter.

4.2.3. Flow meter selection and the influence of the installation location

Due to the different measurement principles of different types of volume flowmeters, the fluid pressure will drop to different degrees through the flowmeters, which may lead to the phase change of CO₂ fluid during the measurement process, thus significantly reducing the accuracy of flow measurement. Especially for the impurity-containing CO₂, the phase transition characteristics are even more complex. Therefore, when measuring the CO₂ flow rate, it is necessary to select the CO₂ flow meter reasonably. If the installation position is not appropriate, it will usually cause the uneven distribution of the pipeline and the pressure change in the pipeline, especially the pressure change. According to the analysis of CO₂ and phase characteristics in 4.2.1, the pressure change may change the CO₂ density in the pipeline and cause inaccurate measurement.

Standard orifice plate flowmeters usually cause a permanent pressure drop [50-51] in practical engineering applications. In addition to the pressure drop problem, the later maintenance cost of the hole plate flowmeter is also higher. In 2004, Marshall Aviation Flight Center proposed a new differential pressure porous hole plate flowmeter, which greatly reduced the fluid pressure drop [52] compared with the standard hole plate. Similar differential pressure flow meter with small pressure loss and V-cone flow meter, both of which are suitable for measuring CO₂ fluid sensitive to pressure drop. The vortex flowmeter is also a flowmeter that will produce similar pressure drop to the standard orifice flowmeter, but due to its special structure, the later maintenance cost is lower than the orifice flowmeter. The pressure drop caused by the turbine flowmeter in the fluid is much less than both [53], which is a good choice for measuring the CO₂ mass flow rate.

During installation, the flow produces strong secondary flow and eddy current in the downstream flow field, resulting in the asymmetric velocity distribution phenomenon, thus affecting the accuracy of the flow measurement. Therefore, it is necessary to install the flow meter at the speed back to the position of the symmetrical distribution. Therefore, first consider the sufficient length of the selected flowmeter according to the standard to ensure that the inner diameter of the connecting pipe matches the nominal diameter of the flow meter, otherwise the error [54-56] will occur to a certain extent. In addition, if there is a valve (such as a pressure reducing valve, etc.) or a bypass pipe near the upstream and downstream of the flowmeter, it will also cause a certain degree of pressure drop, and the phase change may occur. If the flowmeter is installed outdoors, it may be disturbed by ambient temperature. Temperature change cannot interfere with the accuracy of the flowmeter itself, but also affect the density of the CO₂ and thus the meter accuracy. The flowmeter may be affected by common-mode noise (such as RF interference, electromagnetic interference), vibration, corrosive gas and humidity, and also need to keep away from such interference or correction during installation. Since there are many factors affecting CO₂ density, density correction is

required to compensate for the installation position measured with additional processes to make the measurement more accurate. These additional process measurements such as temperature and pressure shall be installed at the installation locations recommended in GB/T 25922-2023/ISO 12764:2017.

In conclusion, when selecting CO₂ flow metering, selecting flow meters that may produce significant pressure drop on the flow should be avoided as far as possible. It is recommended to use the flow meter with a small pressure drop and less impact on the fluid itself, such as turbine flow meter and V-cone flow meter, to consider the economy and improve the measuring accuracy. In the process of CO₂ measurement with impurities, the performance of the flowmeter will be adversely affected by phenomena such as two-phase flow, pipe diameter, velocity distribution, pump noise, inlet throttle noise and so on. Select the meter and the appropriate location of other system components.

5. CO₂ Suggestions for Accurate Measurement Measures of Flow Rate

1. Weighing method

Although the weighing method is simple to operate, easy to implement and wide range, the weighing method can only measure the CO₂ fluid density of specific components. Therefore, in the case of a relatively stable type and content of impurities, the weighing method is more economical and reasonable. However, when the type and content of impurities change, the weighing method is not applicable.

2. Densitometer

Densometer has high measurement accuracy, and fast measurement speed, can obtain real-time fluid density data, suitable for automation in practical engineering applications, suitable for a variety of fluids, but its equipment cost is high, is not suitable for widely used in practical engineering.

3. Density correction

This paper proposes a density correction method to measure the current temperature and pressure near the metering point in real time for the CO₂ with different impurity types and contents. In the measurement, the REFPROP [57] database provided by the National Institute of Standards and Technology (National Institute of Standards and Technology, NIST) can be used to combine the measured temperature pressure to correct the density of the fluid, the real-time density, and calculate the real-time CO₂ mass flow. So as to solve the accuracy problem of CO₂ measurement.

4. The selection of flowmeter

According to the requirements of measurement accuracy in the measurement principle and standard, the mass flow meter should be selected when the first level of measurement is needed, such as: Coriolis mass flow meter. For Level II and III metering, differential pressure or volumetric flow meters are recommended. When selecting the type of volume flowmeter, you can choose the flowmeter with small pressure drop and high economy, such as: turbine flowmeter, vortex flowmeter, etc. Reduce the possibility of the phase transition of the CO₂ fluid by reducing the possible pressure drop of the flowmeter itself. The CO₂ density of different impurity components and contents varies to different degrees with the temperature and pressure, which leads to the inaccurate measurement of CO₂

mass flow. Therefore, according to the selected volume flowmeter, obtain the density of CO₂ fluid and combine the density to obtain the mass flow of CO₂.

5. The selection of the flowmeter installation location

Different flowmeters shall be installed according to the requirements of the installation position in the corresponding national standard. For example, GB/T 25922-2023/ISO 12764:2017, Measurement of Fluid Flow in closed pipeline-Measuring flow with vortex flowmeter installed in the circular section pipe filled with fluid points out that the installation position of the upstream and downstream of the flowmeter, the inner diameter of the straight pipe should match the nominal diameter of the flowmeter, and there should be no valve or bypass pipe near the flowmeter, which may cause phase change of the fluid. Moreover, due to the complex phase properties of CO₂ and the critical temperature near room temperature, phase transitions may occur even when installation according to standards. Therefore, in addition to meeting the relevant standard documents, in order to ensure the CO₂ single phase measurement, it is recommended to conduct the fluid CFD simulation, in order to find a reasonable installation position.

6. Heat insulation and insulation

The heat insulation of the front and rear metering pipelines and the flowmeter body should be done to reduce the heat exchange between CO₂ in the pipe and the outside world, so as to prevent the measurement error caused by the temperature change before or during the measurement.

6. Conclusion

In the current CCUS technology process, Coriolis mass flowmeters are predominantly used in engineering applications for CO₂ flow measurement within injection systems due to their high precision, which meets existing oilfield metrological standards. However, their high cost and pipeline diameter limitations make them unsuitable for large-scale engineering deployment. This study recommends adopting volumetric flow meters such as vortex flow meters and turbine flow meters, which offer advantages including minimal pressure drop, compatibility with large-diameter pipelines, and minimal impact on the phase state of CO₂ fluids.

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