Research on Verification Technology for Continuous Online Monitoring of Carbon Dioxide in the Flat Glass Industry

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Abstract—To ensure the accuracy and reliability of carbon emission data in the flat glass industry and address the lack of calibration technology for continuous online monitoring of carbon dioxide, this study systematically reviews the technical performance indicators, installation requirements and monitoring algorithms of CO_2-CEMS. A 72-hour pilot calibration test was conducted at the kiln exhaust outlet of a flat glass enterprise, comparing and analyzing the CO_2 -CEMS monitoring data with the accounting data obtained by the emission factor method. The results show that the hourly deviations are within ±2.5%, and the average deviation over the 72-hour period is only 0.37%. The study validates the feasibility and data reliability of applying CO_2-CEMS at the kiln exhaust outlet of flat glass production, providing technical support for carbon monitoring pilot projects in the flat glass industry.

1. Introduction

Human activities, particularly the substantial emission of greenhouse gases from industrial production and energy consumption, have been widely recognized as a major driver of contemporary global climate change, exerting profound impacts on human living environments, ecosystems, and socioeconomic development[1].Among all greenhouse gases, carbon dioxide constitutes the largest share, accounting for approximately 77% of total global greenhouse gas emissions[2].With the deepening implementation of the "dual carbon" goals, the accuracy and reliability of carbon emission data in key industries have become crucial for the effective operation of the carbon market. Currently, continuous emission monitoring systems (CEMS) for carbon dioxide have attracted widespread attention in sectors such as power generation, cement, and steel. Relevant studies indicate significant discrepancies between online monitoring and accounting-based methods, with flue gas flow measurement precision and instrument calibration being the primary sources of uncertainty affecting data quality[3-5]. Meanwhile, some research has attempted to enhance the metrological traceability of online monitoring data through theoretical value corrections, comparative testing, and quality assurance systems[6-7]. However, as a typical energy-intensive and high-emission industry, flat glass manufacturing has seen very few pilot studies and verification research on online monitoring. Therefore, conducting research on the verification technology of continuous online CO_2 monitoring for the flat glass industry, and establishing an online monitoring data verification and metrological traceability system covering installation specifications, algorithm validation, data auditing, and comparative evaluation, is of great significance for ensuring the authenticity and accuracy of carbon emission data in the industry and for supporting carbon trading and emission reduction decision-making. In this context, this study aims to: (i) develop a systematic verification protocol for CO_2-CEMS in the flat glass industry, including installation requirements and data validation procedures; (ii) implement a 72-hour pilot test at the kiln exhaust of a commercial flat glass production line; and (iii) evaluate the agreement and uncertainty between CEMS-based monitoring data and emission-factor-based accounting data, thereby providing a methodological reference for future carbon monitoring pilots in this sector.

2. Overview of Continuous Online Carbon Dioxide Monitoring Systems

The continuous online monitoring system for carbon dioxide (CO_2-CEMS) utilizes a CEMS equipped with modules such as CO_2 concentration monitoring to continuously and online measure parameters including CO_2 mass concentration in flue gas, flue gas flow rate, temperature, pressure, and humidity from emission sources, thereby calculating CO_2 emissions in the flue gas. The composition of CO_2-CEMS is shown in Figure 1.

2.1 Technical Performance of the Continuous Online Carbon Dioxide Monitoring System

1) Carbon dioxide concentration

The performance indicators for carbon dioxide concentration measurement include measurement range, indication error, system response time, 24-hour zero drift

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and span drift, accuracy, etc. The relevant performance requirements are as follows:

① Measurement range: The upper limit of the CO_2 volume concentration (volume percentage) measurement shall be within the range of 20% to 25%.

② Indication error: The relative error relative to the certified value of the standard gas shall not exceed ±5%, and the absolute error shall not exceed ±0.5% (CO_2 volume percentage).

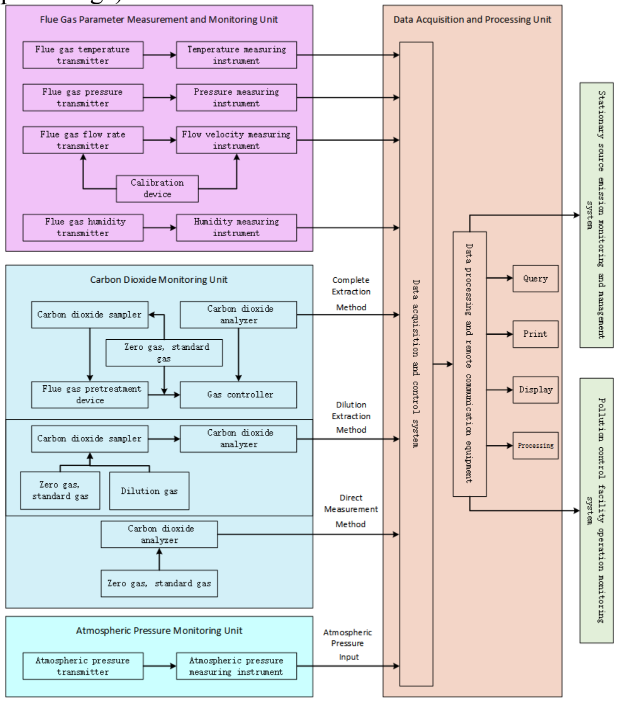

Fig. 1. Schematic diagram of the continuous online carbon dioxide monitoring system composition.

③ System response time: Not greater than 200 s.

④ 24-hour zero drift and span drift: Not exceeding ±2.5% of the full scale.

⑤Accuracy: When the average value of CO_2 concentration in flue gas is measured using a reference method, the accuracy of the measurement results between the CO_2-CEMS and the reference method shall meet the requirements of Table 1.

Table 1. Technical performance requirements for Carbon dioxide concentration.

CO_2 concentration	Accuracy requirement
$20\% \le c_s$	Absolute value of relative error ≤ 10%
$14\% \le c_s < 20\%$	Absolute value of relative error ≤ 2%
$7\% \le c_s < 14\%$	Absolute value of relative error ≤ 1.5%
$c_s < 7\%$	Absolute value of absolute error ≤ 1%

2) Flue gas flow rate

The performance indicators for flue gas flow rate measurement include measurement range, precision or correlation coefficient of the velocity field coefficient, accuracy, etc. The relevant performance requirements are as follows:

① Measurement range: The upper measurement limit shall not be less than 30 m/s.

② Precision or correlation coefficient of the velocity field coefficient: The precision of the velocity field coefficient shall not exceed 5%. If the precision of the velocity field coefficient does not meet the requirement, and the number of valid data pairs consisting of reference method measurement results and flow CMS measurement results is not less than 9, the correlation coefficient shall not be less than 0.9.

③ Accuracy: Using the reference method to measure the average value of the flue gas flow rate, the accuracy of the average flow rate measurement result relative to the average reference method measurement result shall meet the requirements of Table 2.

Table 2. Technical performance requirements for flue gas flow rate.

Flue gas flow rate	Accuracy requirement
$\bar{v} > 10$ m/s	Relative error ≤ ±10%
$\bar{v} \le 10$ m/s	Relative error ≤ ±12%

3) Flue gas temperature

The performance indicator for flue gas temperature is mainly accuracy. The absolute error between the average temperature measurement result and the average reference method measurement result shall not exceed ±3 °C.

4) Flue gas humidity

Using the reference method to measure the average absolute humidity of flue gas, the accuracy of the average humidity measurement result relative to the average reference method measurement result shall meet the requirements of Table 3.

Table 3. Technical performance requirements for flue gas humidity.

Flue gas humidity	Accuracy requirement
$X_{sw} > 5.0\%$	Absolute value of relative error ≤ 2.5%
$X_{sw} \le 5.0\%$	Absolute value of absolute error ≤ 1.5%

2.2 Installation requirements for the CO_2 continuous online monitoring system

The CO_2-CEMS cabinet shall be installed in the monitoring station room. The CO_2 concentration monitoring unit may be added to the existing pollutant CEMS cabinet, or a CO_2 analysis cabinet may be added to the existing pollutant CEMS monitoring station room, or a dedicated CO_2-CEMS monitoring station room may be provided.

The installation position of the CO_2 -CEMS shall meet the following requirements:

1) The installation position shall be located downstream of the stationary source pollution control device and upstream of the comparative monitoring 断面 (cross-section).

2) The location shall be free from interference by ambient light and electromagnetic radiation.

3) The vibration amplitude of the flue duct shall be as small as possible.

4) The installation position shall avoid interference from water droplets and water mist in the flue gas as much as possible. If such interference cannot be avoided, suitable detection probes and instruments shall be selected.

5) The installation position shall be airtight (no air leakage).

6) In the working area where the CO_2 -CEMS is installed, a waterproof low-voltage distribution box shall be provided, equipped with a residual current operated protective device and no less than two 10 A sockets to ensure the power supply for the monitoring equipment.

7) The arrangement of the sampling platform and sampling ports shall comply with the relevant requirements of the Technical Specification for Continuous Monitoring of Flue Gas (SO_2, NO_x, Particulate Matter) Emissions from Stationary Sources (HJ 75-2017).

8) The layout of the monitoring station room shall comply with the relevant requirements of the Technical Specification for Continuous Monitoring of Flue Gas (SO_2, NO_x, Particulate Matter) Emissions from Stationary Sources (HJ 75-2017).

The sampling position shall avoid locations with flue bends and abrupt changes in cross-section. Priority shall be given to vertical pipe sections and negative pressure zones of the flue to ensure the representativeness of the sampled flue gas. For circular flues, the flow velocity measurement cross-section shall be located at a distance of no less than 4 times the flue diameter downstream from bends, valves, and reducers, and no less than 2 times the flue diameter upstream from such components. The CO_2 -CEMS concentration monitoring cross-section shall be located at a distance of no less than 2 times the flue diameter downstream from bends, valves, and reducers, and no less than 0.5 times the flue diameter upstream from such components. For rectangular flues, the equivalent diameter shall be used.

For newly constructed stationary sources, the sampling platform shall be designed and constructed simultaneously with the exhaust device to ensure that the sampling cross-section meets the above requirements. For existing stationary sources where no suitable sampling position can be found, the CO_2 -CEMS sampling or analysis probe shall be installed at a cross-section with stable airflow, and corresponding measures shall be taken to ensure relatively uniform flue gas distribution across the monitoring cross-section and the absence of turbulence.

The uniformity of flue gas flow distribution across the cross-section is determined using the relative root mean square method: when $\sigma_r \leq 0.15$, the gas flow is considered uniformly distributed. σ_r is calculated according to Equation (1).

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^{n}(v_i-\bar{v})^2}{(n-1)\times\bar{v}^2}} \tag{1}$$

where σ_r is the relative root mean square of flow velocity, v_i is the flue gas flow velocity at measuring point i (in m/s), $\bar{v}$ is the average flue gas velocity across the cross-section (in m/s), and n is the number of velocity measuring points on the cross-section.

To facilitate the verification and comparative monitoring of the flow velocity reference method, the flow velocity monitoring probe should preferably be installed at a location where the flue gas velocity is not less than 5 m/s.

If the exhaust from a stationary source first passes through multiple flues or ducts before entering the main exhaust pipe of the source, the CO_2-CEMS should be installed as far as possible on the main exhaust pipe, provided that the measurement results can be conveniently verified using the reference method. The CO_2-CEMS shall not be installed on only one of the flues or ducts, with the measured value taken as the CO_2 emission result of the stationary source. However, CO_2-CEMS may be installed on each flue or duct, in which case the total CO_2 emission shall be the sum of the measured values from all flues or ducts.

If a carbon dioxide capture device is installed downstream of the stationary source pollution control equipment, CO_2-CEMS shall be installed on the main exhaust pipe downstream of the carbon dioxide capture device and on the exhaust pipe of the carbon dioxide capture device. The total CO_2 emission shall be the sum of the measured values from both devices.

3. Algorithm for continuous online monitoring of carbon dioxide

The advantages of continuous online monitoring of CO_2 include the highest data timeliness (hourly or even minute-level), facilitating the detection of abnormal fluctuations; high automation with remote data transmission, reducing manual intervention; and no need for additional sampling in multi-fuel co-firing scenarios, offering better adaptability. The CO_2 continuous online monitoring system directly measures flue gas parameters in the stack of the kiln and calculates the CO_2 emission mass rate and cumulative emissions in real time. The core algorithm is based on the principle of mass conservation, multiplying the dry-basis mass concentration of CO_2 in the flue gas by the dry-basis flue gas volume flow rate at standard conditions to obtain the CO_2 emission mass per unit time.

1) Carbon dioxide concentration

The CO_2 concentration directly measured by CEMS is a volume fraction, which is converted to mass concentration using Equation (2).

$$c_d = c_s \times \frac{44}{22.4} \times 10^{-2} \tag{2}$$

where c_s is the dry-basis volume fraction of CO_2 measured by the CEMS system (in %), andc_d is the dry-basis mass concentration of CO_2 at standard conditions (in kg/m³).

(2) Flue gas flow rate

The actual wet flue gas volume flow rate is calculated using Equation (3).

$$Q_s = 3600 \times F \times \bar{v} \tag{3}$$

where Q_s is the measured wet flue gas volume flow rate (in m³/h), F is the area of the measurement cross-section (in m²), and $\bar{v}$ is the average wet flue gas velocity at the measurement cross-section (in m/s).

The dry flue gas volume flow rate at standard conditions is calculated using Equation (4).

$$Q_{sn} = Q_s \times \frac{273.15}{273.15+t_s} \times \frac{p_{atm}+p_s}{101.325} \times (1 - X_{sw}) \tag{4}$$

where Q_{sn} is the dry flue gas volume flow rate at standard conditions (in m³/h), t_s is the flue gas temperature (in °C), P_s is the static pressure of flue gas (in kPa), P_{atm} is the atmospheric pressure (in kPa), and X_{sw} is the water vapor content of flue gas (in %).

3) CO_2 emission mass rate

The CO_2 emission mass rate is calculated using Equation (5).

$$E_h = c_d \times Q_{sn} \times 10^{-3} \tag{5}$$

where E_h is the CO_2 emission mass rate (in t/h).

4) Daily total CO_2 emission of the enterprise

The daily total CO_2 emission of the enterprise is calculated using Equation (6).

$$E_d = \sum_{h=1}^{24} \overline{c_{dh}} \times Q_{snh} \times 10^{-3} \tag{6}$$

where$E_d$is the daily CO_2 emission (in t), Q_{snh} is the dry flue gas flow rate at standard conditions during hour h (in Nm³/h), and $\overline{c_{dh}}$ is the dry-basis mass concentration of CO_2 measured during hour h (in kg/m³).

4. Verification analysis of continuous online monitoring data for CO_2

A pilot test of continuous online CO_2 monitoring was carried out on the stack at the kiln exhaust of a flat glass enterprise. The production line under test had a capacity of 600 metric tons per day, employing a regenerative cross-fired furnace fueled primarily by natural gas The kiln exhaust temperature ranged from 160 to 180 °C, and the flue gas velocity at the measurement cross-section was approximately 10–14 m/s. Direct CO_2 emission monitoring data from the CEMS were collected over a 72-hour period in advance from the pilot enterprise. Meanwhile, activity data and emission factors for the kiln accounting-based emissions were collected for the same time period

The emissions from the monitoring-based method and the accounting-based method were compared and verified. The data comparison is shown in Figure 2, and the daily deviation comparison is presented in Table 4.

Table 4. Daily deviation comparison between accounting data and CEMS monitoring data.

Day	Accounting data (tCO_2)	CEMS monitoring data (tCO_2)	Deviation (%)
Day 1	256.92	257.98	-0.41%
Day 2	260.82	258.76	0.80%
Day 3	264.32	262.42	0.72%

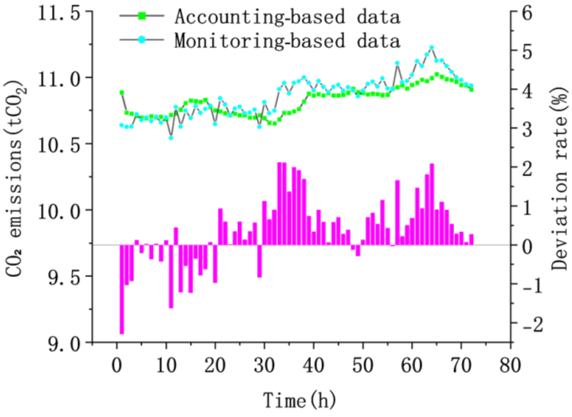

Fig. 2. Comparison between accounting data and CEMS monitoring data.

Through comparative verification analysis, it can be seen that the overall trend of CEMS monitoring data is consistent with that of the accounting data, indicating that the two independent methods respond synchronously to changes in kiln load or fuel consumption, thereby validating the capability of CEMS to dynamically track actual emission processes. The hourly deviations are all within ±2.5%, and the average deviation over the 72-hour period is only 0.37%, far better than the typical deviation ranges observed in current carbon monitoring pilots in industries such as power generation, cement, and steel. This indicates that the CEMS system adopted by the pilot enterprise has achieved a high level of performance in installation, calibration, operation, and maintenance.

5. Discussion

The high consistency observed between CEMS monitoring data and accounting data (average deviation 0.37% over 72 hours, with hourly deviations within ±2.5%) demonstrates that properly installed and maintained CO_2-CEMS can accurately track CO_2 emissions from flat glass kilns. This level of agreement surpasses typical deviations reported in power and cement industry pilots (often in the range of 5–10%), which may be attributed to the stable combustion conditions and relatively uniform flue gas flow in the glass melting furnace examined. However, several limitations should be noted. First, the study was conducted on a single production line over a limited 72-hour period, and longer-term performance under varying operational loads or fuel switching remains to be verified. Second, the accounting method used emission factors with inherent uncertainties that were not fully quantified in this comparison. Third, the CEMS accuracy relies critically on flow rate measurement precision and regular calibration, which may degrade over time. Future work should extend the monitoring duration, incorporate multiple kiln types and fuel mixes, and develop a robust uncertainty budget for both CEMS and accounting methods to strengthen confidence in carbon monitoring data for the flat glass industry.

6. Conclusions

This study systematically reviews the technical performance indicators and installation requirements of the continuous online monitoring system for carbon dioxide, specifying the accuracy requirements for key parameters such as CO_2 concentration, flue gas flow rate, temperature, and humidity, as well as the specifications for sampling locations. It also elaborates on the carbon emission monitoring algorithm based on dry-basis mass concentration and dry flue gas volume flow rate at standard conditions. On this basis, through a pilot verification at the kiln exhaust of a flat glass enterprise, the CEMS monitoring data were compared with the accounting-based data. The results show that the hourly deviations are all within ±2.5%, and the average deviation over 72 hours is only 0.37%, validating the feasibility and data reliability of CEMS application at the kiln exhaust of flat glass enterprises. This provides technical support and a data basis for the transition of carbon monitoring in the industry from an “accounting-dominant” approach to a dual-track system combining accounting and monitoring.

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