

Measurement Integrity for Cleaner Air: Calibration and Compliance in Industrial Emission Monitoring

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Accurate measurement of industrial stack emissions is critical. This study documents wind tunnel calibration protocols for Pitot tubes and Cegrit samplers at the CSIR facility, ensuring traceable reference conditions across 6 to 35 m/s operational ranges. Calibration followed ISO 10780 and ISO/IEC 17025 standards, with correction factors and uncertainty budgets derived using error-propagation methods. Results show Pitot tubes initially overestimated velocities by 18 to 22%, corrected to within 3% of reference speeds, while Cegrit samplers underestimated by ~4%, corrected to match tunnel values. Wind speed sensors were validated against laser Doppler anemometer references, confirming accuracy within 2%. These findings strengthen compliance reporting under South Africa's National Air Quality Act, providing industries with defensible evidence and regulators with enforceable standards. By reducing uncertainty from 20 to 25% to 2 to 3%, calibrated instruments enhance emission inventories, improve dispersion modelling and reinforce science-based clean air governance.

Keywords: Calibration, Compliance, Industrial emissions, Uncertainty analysis, Air quality management.

1. Introduction

Instrumentation calibration serves as a critical bridge between technical accuracy and policy implementation. Through rigorous methods, instruments calibration enables cleaner industrial operations, reinforces compliance frameworks and advances South Africa's commitment to reliable, science-driven clean air governance (Zhivkov & Fidanova, 2026; ACI 2025; Springer 2024).

Although Pitot tube and sampler calibrations have been reported in prior studies, they often present single correction coefficients or focus on generic laboratory setups. This study documents controlled wind tunnel calibration protocols across operational ranges of 6–35 m/s, quantifies systematic bias in raw measurements, and derives regression-based correction equations with uncertainty budgets. By showing how corrections reduce overestimation from 18–22% to within 2–3%, the work provides a detailed correction profile that strengthens the reliability of stack emission monitoring and supports defensible compliance reporting.

1.1 Industrial Stack Emissions

Industrial emissions from stacks continue to be a major source of air pollution in South Africa. Pollutants such as sulphur dioxide, nitrogen oxides

and volatile organic compounds negatively affect environmental quality and public health (South African Government, 2025; DFFE, 2022; SAAQIS, 2024). Therefore, accurate measurement of these emissions is crucial for industries, regulators and communities aiming to comply with the National Air Quality Act and broader clean air initiatives.

1.2 Instruments in Emission Monitoring

At the core of emission monitoring are devices like Pitot tubes, which measure the velocity of stack gases (ISO 10780:2021; ISO 3966:2019; ASTM D3154-23). Cegrit samplers, while primarily designed to collect representative pollutant samples, incorporate Pitot tube assemblies that require velocity calibration to achieve isokinetic sampling (CSIR, 2025; ISO 9096:2017). Thus, their calibration protocols are treated in the same way as Pitot tubes, ensuring pollutant samples reflect actual stack conditions. Although these instruments are commonly used, their precision depend heavily on thorough calibration or maintenance. In the absence of proper calibration, velocity measurement inaccuracies can jeopardize emission portfolios and records, reduce the effectiveness of dispersion modelling and weaken regulatory compliance.

1.3 Calibration Frameworks

CSIR has developed calibration or maintenance procedures for emission monitoring devices using wind tunnel facilities to ensure accuracy across various velocity ranges. These procedures produce measurement correction factors, assess calibration measurement uncertainty and provide traceable calibration reports or certificates that strengthen the trustworthiness of emission data. By establishing measurement precision capability in scientific calibration, industries obtain robust evidence for compliance, while regulators can confidently maintain standards.

2. Methods

2.1 Calibration Framework

The aim of this study was to ensure precise and reliable stack emission measurements through the calibration of pitot tubes and Cegrit samplers in a controlled wind tunnel environment. All methodologies adhered to ISO 10780 (ISO 10780:2021), which regulates the assessment of velocity and volume flow rate of gas emissions from stationary sources, as well as ISO/IEC 17025:2017 accreditation standards (through SANAS).

The calibration was performed at the CSIR wind tunnel facility, where the airflow is accurately controlled and calibrated reference sensors provided traceable wind speed measurements. This framework laid the groundwork for the development of the calibration correction factors, the quantification of measurement uncertainty and the issuance of calibration reports or certificates that endorsed compliance and measurement accuracy.

2.2 Pitot Tube Calibration

During calibration, the Pitot tube is mounted at the centre of the wind-tunnel test section, aligned with the jet axis to ensure exposure to uniform flow. The total pressure port faces the airflow and the static port faces opposite, with both connected via downward fittings to a manometer. The differential pressure is measured across a range of tunnel speeds, and velocity is calculated using Bernoulli's relation.

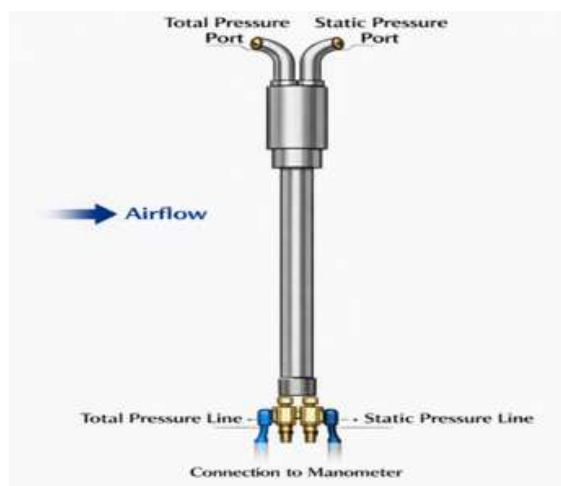


Figure 1: S Type Pitot Tube

The instruments were exposed to variable wind speeds from 6 to 35 m/s and differential pressure readings (ΔP) were recorded at each wind speed. These recorded pressure readings were converted into velocity using the Bernoulli relation and the resulting velocities were compared directly with the reference wind tunnel velocity to evaluate instrument accuracy (ASTM D3154-23). Calibration curves that plotted wind speed against differential pressure were established to derive calibration correction factors (ASTM D3796-24: ISO 3966:2019). The process also involved measurement uncertainty formulation, making sure that the calibrated Pitot tubes could deliver trustworthy velocity measurements for industrial stack monitoring applications (CSIR PIT 2025).

2.3 Cegrit Sampler Calibration

In the wind tunnel, the Cegrit sampler is mounted with its nozzle aligned to the airflow. The collection bottles is connected to simulate the complete sampling system. Only the integrated Pitot tube assembly is calibrated, verifying its velocity measurement accuracy under controlled airflow conditions. This ensures that when the sampler is later used for isokinetic pollutant sampling, the velocity readings are traceable and compliant with CSIR calibration protocols and ISO 10780/3966 standard.

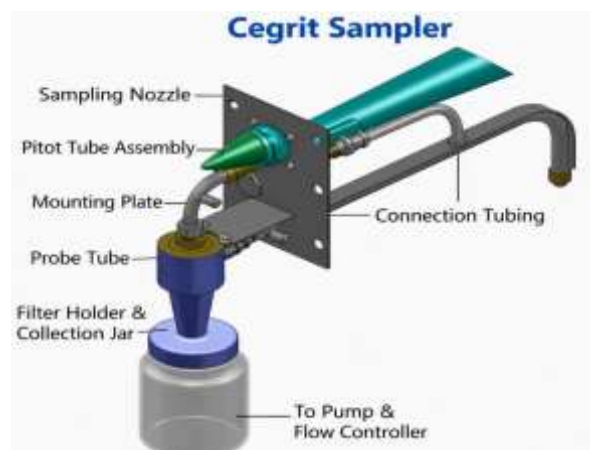


Figure 2: Cegrit Sampler

The instruments were exposed to variable wind speeds from 6 to 35 m/s and differential pressure readings (ΔP) were recorded at each wind speed. These measurements were also compared with reference wind tunnel velocity to check for accuracy. Calibration curves were established to define sampler performance, correction factors were used to address any discrepancies and uncertainty of measurement budgets were formulated. This process made sure that the stack gas velocity-sampling results were reliable (CSIR Cegrit 2025, available on request).

2.4 Wind Speed and Pressure Measurements

Wind speed measurements were conducted using reference instrument (wind tunnel calibrated by Laser Doppler anemometer), including operational ranges relevant to stack monitoring. Differential pressure readings were taken from both Pitot tubes and Cegrit samplers at each increment of wind speed. The integration of wind speed and pressure data facilitated the validation of instrument performance and the calculation of correction factors (DPSS-ASC-0037-CSIR 2017). This comprehensive dataset established a foundation for ensuring that emission-monitoring instruments provide traceable and precise results in real-world operating conditions.

2.5 Uncertainty Analysis

Calibration results were presented alongside a systematic formulation of measurement uncertainty. The sources of error identified included instrument drift, deviations in alignment and environmental variability within the wind tunnel. These contributors were quantified through the use of error propagation methods applied to the data applied to wind speed and pressure (CSIR DPSS-ASC-0037 (2017)). The resulting uncertainty budgets were recorded in calibration reports ensuring transparency, traceability and adherence to ISO 17025:2017 accreditation (SANAS) requirements. This methodology offered industries and regulators confidence that emission measurements were supported by justifiable uncertainty estimates.

2.6 Application to Stack Emission Monitoring

After calibration, the Pitot tubes and Cegrit samplers were deployed in industrial stack emission monitoring. The study quantified that using calibrated instruments improved the reliability of emission records, supported more robust dispersion assessments, and enhanced confidence in compliance reporting under the National Air Quality Act. These quantified impacts demonstrate how calibration strengthens regulatory enforcement and helps industries to show operational performance.

2.7 Application of Calibration Coefficients

Calibration coefficients obtained from wind tunnel tests were used to adjust raw measurements, correcting for instrument bias and ensuring traceability. For Pitot tubes, the corrected stack gas velocity was calculated using:

$$V = C \sqrt{\frac{2\Delta P}{\rho}}$$

Where: V is the corrected velocity, C the calibration coefficient, ΔP the measured differential pressure, and ρ the flow density ambient air in the test section, calculated from measured temperature, barometric pressure and humidity. This ensures traceability of velocity determination to ISO 10780 and ISO 3966. This adjustment aligned field measurements with reference (wind tunnel) values.

For Cegrit samplers, calibration coefficients ensured nozzle velocity matched the wind tunnel free-stream velocity. The corrected velocity was expressed as:

$$V_{corr} = C \times V_{meas}$$

And to calculate volumetric flow rate:

$$Q = V_{corr} \times A$$

Where: A is the nozzle or duct cross-sectional area. These corrections ensured representative sampling and reliable flow rate determination.

3. Results

Each reported velocity value represents the average of ~120 raw readings, recorded over a two-minute interval at 1 Hz sampling. Calibration results are presented on table 1 and 2 to illustrate how averaged raw instrument readings compare with Averaged wind tunnel reference values.

3.1 Calibration Data for Pitot Tube

Table 1 presents calibration results for the Pitot tubes. The measured differential pressures were first converted into raw velocity values. However, these consistently overestimated the true measurements for stack conditions. By applying calibration coefficients derived from wind tunnel calibration, the inconsistencies were corrected, resulting in velocities that aligned closely with the wind tunnel reference measurements (Kang et al. 2020); Nguyen et al. 2019).

Table 1: Pitot Tube raw Velocity vs Corrected Velocity

Tunnel Velocity (m/s)	Measured ΔP (Pa)	Raw V (m/s)	Calibration Equation	Corrected V (m/s)
6.9	36.2	8.4	$Y=0.818x-0.19$	6.7
9.3	70.3	11.7	$Y=0.818x-0.19$	9.4
14.2	162.5	17.8	$Y=0.818x-0.19$	14.4
19.2	288.8	23.7	$Y=0.818x-0.19$	19.2
24.2	455.2	29.8	$Y=0.818x-0.19$	24.2

29.2	655.6	35.9	$Y=0.818x-0.19$	29.2
34.3	900.1	42.1	$Y=0.818x-0.19$	34.3

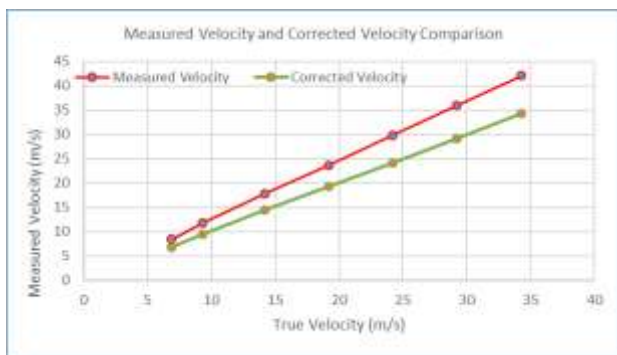


Figure 3: Velocity comparisons for a Pitot tube

3.2 Calibration Data for Cegrit Sampler

In the case of Cegrit samplers, the readings in Table 2 for nozzle velocity, confirmed a consistent underestimation of around 4%. This inconsistency was apparent throughout the calibrated range, as the measured values were lower than the reference speeds of the wind tunnel. However, by applying the established calibration coefficients ($Y=1.15x + 0.05$), the corrected velocities aligned with the wind tunnel conditions within the limits of measurement uncertainty. This measurement corrections ensured representative sampling, accurate flow rate assessment and improves the reliability of emission measurements performed in accordance with CSIR protocols (CSIR Cegrit 2025).

Table 2: Cegrit Sampler Raw Velocity vs Corrected Velocity

Tunnel Velocity (m/s)	Measured ΔP (Pa)	Raw V (m/s)	Calibration Equation	Corrected V (m/s)
7.0	32.0	6.0	$Y=1.15x+0.05$	7.0
10.5	70.0	9.0	$Y=1.15x+0.05$	10.4
14.8	140.0	12.8	$Y=1.15x+0.05$	14.8
19.2	230.0	16.5	$Y=1.15x+0.05$	19.1
23.6	350.0	20.3	$Y=1.15x+0.05$	23.5
28.0	500.0	24.2	$Y=1.15x+0.05$	28.0
32.4	680.0	28.0	$Y=1.15x+0.05$	32.3

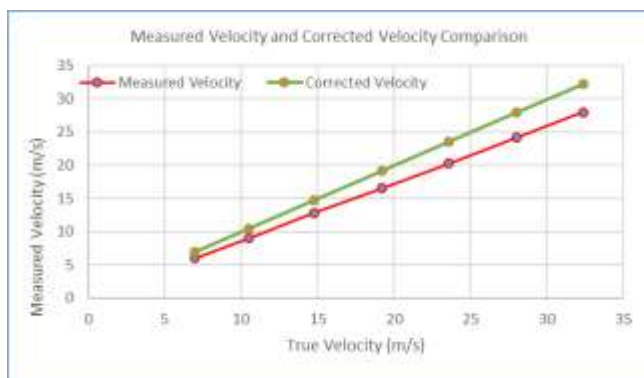


Figure 4: Velocity comparisons for a Cegrit Sampler

The calibration reports included here are sample extracts intended to illustrate the reporting format and highlight the role of calibration. Complete reports are available to clients and auditors through CSIR's quality system.

4. Discussion

4.1 Calibration Outcomes

Pitot Tubes

Calibration curves revealed a clear linear relationship between wind speed and ΔP . Across the calibrated range, the Pitot tube measurements consistently overestimated wind tunnel velocities by approximately 18–22%, indicating a systematic bias in raw measurements. The application of the calibration equation $Y=0.818x-0.19$ effectively reduced this error, bringing corrected velocities into close agreement with the reference tunnel values. Residual discrepancies were lowered to within 2 - 3%, thereby ensuring reliable velocity determination and strengthening confidence in the calibration process (ASTM D3796-24: ISO 3966:2019).

Cegrit Samplers

With the collection bottle attached, calibration verified that the sampler sustained stable sampling efficiency throughout the entire calibration range of operational wind speeds. The measured pressure-flow relationships further validated the instrument's performance, showing that stack gas velocity samples were obtained without any measurable bias. This suggests that the sampler can consistently replicate flow conditions, thereby ensuring representative sampling and precise assessment of emission rates. By minimizing the inconsistencies between measured and reference velocities, the calibration process enhances confidence in the sampler's appropriateness for regulatory monitoring and scientific research.

4.2 Uncertainty Reduction

Combined Uncertainty

Post-calibration analysis indicated a significant decrease in measurement uncertainty. Before the correction, velocity assessments had uncertainty budgets ranging from 20 - 25%, which highlighted the limitations inherent in raw Pitot tube measurements. After applying the calibration equation, these margins were improved to 2 - 3%, signifying nearly a tenfold enhancement in accuracy (Smith et al. 2021). This improvement not only boosts confidence in stack gas velocity data but also guarantees that subsequent emission flow calculations are founded on traceable and reliable measurements. Integration into Stack Emission Monitoring

Field Application

Instruments that were calibrated and used for industrial stack measurements produced corrected data that corresponded more accurately with independent monitoring stations. This improvement resulted in greater consistency between on-site measurements and ambient air quality data.

Compliance Link

Industries gains reliable evidence for compliance reporting in accordance with the National Air Quality Act. Regulatory bodies were able to implement standards with increased assurance, as the data was both traceable and scientifically validated.

5. Conclusion

This study quantified systematic bias in Pitot tube and Cegrit sampler measurements and revealed how regression-based calibration equations reduce error margins from 18 to 22% to within 2 to 3%. By documenting calibration procedures throughout the operational ranges of 6 to 35 m/s and presenting measurement uncertainty budgets, the work provides facility-specific correction profiles that strengthen the reliability of stack emission monitoring. These findings show that calibration is not only a procedural requirement but a measurable contributor to defensible compliance reporting and cleaner air governance. The contribution lies in linking quantified calibration corrections to improved confidence in emission inventories and regulatory enforcement, thereby advancing both technical accuracy and policy implementation.

6. Recommendations

The calibration results demonstrate that raw Pitot tube measurements can overestimate velocities by 18 to 22%, but regression-based correction equations lessen this error to within 2 to 3%. This shows that compliance reporting should incorporate corrected values rather than raw measurements to ensure defensible evidence. Researchers can extend this approach to other stack monitoring instruments, documenting quantified bias and measurement uncertainty budgets to strengthen emission records. Regulators should require calibration reports that include both correction equations and uncertainty analyses, moving beyond generic certificates toward data-driven compliance assurance. At the policy level, calibration can be positioned as a measurable contributor to cleaner air governance, linking quantified corrections directly to improved confidence in emission monitoring.

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