CHARACTERISATION OF CSIR's OPEN-JET 2-METER WIND TUNNEL FOR IEC 61400 MEASNET-COMPLIANT CALIBRATION OF CUP ANEMOMETERS

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Abstract

Accurate measurement of wind speed is essential for effective assessment of wind resources and evaluation of turbine performance within the wind energy industry. This paper details the characterization of the Council for Scientific and Industrial Research (CSIR) open-jet 2-meter wind tunnel, which is designed to facilitate MEASNET-compliant calibration of cup anemometers in line with IEC 61400. The test section underwent a rigorous evaluation to determine flow uniformity, turbulence intensity, and both axial and vertical flow alignment, utilizing a grid of calibrated pitot tubes. Measurements were taken across various horizontal and vertical planes to evaluate the spatial velocity distribution and confirm compliance with international calibration standards.

The open-jet design presents distinct aerodynamic challenges, especially in maintaining low turbulence and uniform velocity profiles in the wind tunnel test section. Through a process of iterative flow conditioning and systematic testing, the tunnel achieved velocity deviations within ±0.03 m/s, thereby complying with the rigorous criteria for high-precision anemometer calibration. Repeatability tests conducted with a reference anemometer, along with assessments of environmental stability, further substantiated the wind tunnel's performance under different ambient conditions. The findings affirm the tunnel's capability as a national calibration facility, providing traceable and internationally recognised wind speed measurement capabilities. This characterisation establishes a basis for future improvements, including broader calibration ranges, automated testing rigs, and integrated uncertainty modelling to meet the increasing demands of the wind energy sector. This characterisation lays the groundwork for future upgrades, like wider calibration ranges, automated calibration systems, and better uncertainty modelling, to keep up with the growing needs of accurate measurements within the wind energy industry.

Keywords

Wind tunnel, Characterisation, Cup anemometer calibration, Flow uniformity, Pitot tube measurements

I. INTRODUCTION

CSIR operates state-of-the-art wind tunnel facilities dedicated to the aerodynamic testing of various artefacts. Among these facilities is the open jet 2-meter wind tunnel (2mWT), which features a 78-kW fan-driven system capable of achieving wind speeds of up to 35 m/s. The open test section of the 2mWT measures 1.7 m in diameter and 2.5 m in length, and it has been utilized for testing propellers, car models, and aero foils.

Currently, the wind energy sector has increasingly depended on cup anemometers as the primary reference standard for measuring wind speed. These devices are essential in various applications, including weather monitoring, wind farm optimization, aviation operations, and environmental studies, all of which require high-precision data. To ensure measurement accuracy, cup anemometers must undergo periodic calibration. MEASNET, which was established in 1997, created the IEC 61400 standard to promote consistent calibration practices. Members of MEASNET are required to be ISO/IEC 17025:2017 accredited in their respective countries to conduct compliant measurements.

Nevertheless, open jet tunnels such as the CSIR's 2mWT are susceptible to environmental variations, which complicates the control of wind speeds below 6 m/s without modifications. Achieving stable measurements at low speeds may require prolonged waiting periods. Furthermore, CSIR's accredited laboratory is currently unable to facilitate cup anemometer calibration due to constraints related to blockage ratios. The MEASNET standard stipulates a blockage ratio of less than 10%, a 13-point calibration between 4 m/s and 16 m/s, and a correlation factor of 0.99994. Other vital parameters include low turbulence, uniform flow, and minimal angular deviation.

At present, no facility in Africa provides MEASNET-compliant cup anemometer calibration, compelling developers in the wind energy industry to send their instruments abroad, and a costly and time-consuming effort. Characterizing the CSIR 2mWT for this purpose could diminish the dependence on international laboratories and establish a MEASNET-compliant calibration facility locally.

Objectives of this study include:

- Evaluating the performance of the 2mWT across the 4–16 m/s range required for cup anemometer calibration
- Developing a repeatable and reliable experimental methodology that meets MEASNET proficiency testing standards
- Assessing the time required to complete the calibration of a single cup anemometer

II. Background and Literature Review

Wind Energy and the Role of Cup Anemometers

The worldwide transition to renewable energy has heightened the necessity for precise wind resource assessment and turbine performance assessment. Cup anemometers continue to be the benchmark in the industry for measuring wind speed, owing to their straightforward design, dependability, and cost efficiency. The calibration of these devices is essential for maintaining data integrity in various applications, from optimizing wind farms to forecasting meteorological conditions. To standardize calibration methods, the IEC 61400-12-1 standard was established with the support of MEASNET (Measuring Network of Wind Energy Institutes). These standard outlines rigorous requirements for wind tunnel calibration, which include:

- A 13-point calibration conducted between wind speeds of 4 m/s and 16 m/s
- A blockage ratio that does not exceed 10%
- Flow uniformity, low turbulence intensity, and minimal angular deviation
- A correlation coefficient of no less than 0.99994 between reference and test anemometers.

These specifications guarantee that calibrated anemometers provide consistent and traceable measurements across various facilities.

Wind Tunnel Calibration Challenges

Calibrating cup anemometers in a wind tunnel comes with its own set of aerodynamic hurdles. Hansen et al. point out that issues like tunnel boundary interference and rotor proximity can skew calibration results, particularly in smaller or open-jet tunnels [3]. To prevent mistakes in measuring rotor torque and tilt response, it's crucial to keep the flow uniform and reduce turbulence. Open-jet wind tunnels, such as CSIR's 2mWT, are especially prone to changes in the environment. When trying to maintain stable flow at low wind speeds (less than 6 m/s), it often takes a long time to stabilize. Plus, the open design can cause uneven velocity profiles and greater angular deviations, making it harder to meet MEASNET standards.

CSIR's Wind Tunnel Infrastructure

The CSIR operates a suite of wind tunnels, including the 2mWT (open-jet), designed for low-speed aerodynamic testing. The 2mWT features:

- A 78-kW fan system capable of reaching speeds up to 35 m/s
- A 1.7 m diameter and 2.5 m long open test section
- Historical use in testing propellers, vehicle models, and pressure measurements [4]

Even with its versatility, the 2mWT has not yet been accredited for MEASNET-compliant calibration due to blockage ratio constraints and environmental variability. Characterizing the tunnel for this purpose could establish Africa's first local calibration facility, reducing reliance on overseas laboratories and supporting regional wind energy development.

Recent Research and Methodologies

Recent studies have emphasized the importance of flow conditioning and grid-based pitot tube measurements to assess flow quality. The MEASNET Calibration Procedure (Version 3, 2020) provides detailed guidance on [4]:

- Flow uniformity testing using a grid resolution ≤15 cm
- Stability assessments at 4, 8, 12, and 16 m/s
- Horizontal wind gradient evaluations to detect flow asymmetries [2]

Other researchers have proposed alternative calibration methods to reduce uncertainty in wind power density estimation, such as dynamic pressure-based models and rotor geometry optimization [5].

III. Methodology

Test facility description

The 2-meter Wind tunnel facility within the CSIR is classified as an open jet subsonic wind tunnel with speeds from 4 m/s to 35 m/s. It is a continuous open circuit powered by a 78kW fan. The wind tunnel facility has been mainly used for research and training. The inlet of the tunnel has an array of square flow straighteners

Instrumentation

Five pitot static tubes were used to measure the pressure. Four probes were mounted on the duct inlet to measure the pressure as it enters the test section, and a reference pitot was placed at the Centre of the test section relative to the duct inlet to correct the velocity. A Campbell Scientific CR1000X data logger was used to measure the frequency of two cup anemometers that were used for verification. The environmental conditions were measured using a P650 Handheld thermometer, a DPI620 pressure calibrator and a 9535 VelociCalc for humidity. A transverse system has been developed to measure the flow uniformity at the center of the test section where the cup anemometers are installed.

Procedures

1. The MATLAB software program was developed to:
   - Iterate the required deviations at each point of calibration that can meet the MEASNET calibration coefficient of 0.99994.
   - determine the time that is required at each point of calibration (4m/s-16m/s) to assess the mean average that is sufficient to deem the data valid.
2. The pitot tubes were connected to a ZOC3000 10-inch of water Scanivalve pressure scanner module to measure the total and static pressure, which is used to calculate the dynamic pressure on each tube, and an average was taken for the four-duct inlet pressure. The wind tunnel velocity in the test section was calculated using the Bernoulli equation. The blockage of the

cup anemometer was calculated by dividing the area that the cups cover by the area of the test section

3. A calibrated pitot tube was used as a reference standard. This was installed in the tunnel test section where the cup anemometer is installed. The correction factor of this device was used to correct the mean velocity from the duct inlet to the test section. The results of the two cup anemometers obtained from the Campbell Scientific data logger CR1000X were compared against the proficiency testing results conducted in 2016 and 2024, respectively.

IV. Results and Analysis

Deviation Factor Analysis Results

Using MATLAB code to predict the required deviation of the unit under test, it was determined that the deviation of the velocity at each point of estimation should be less than or equal to 0.12. This can be seen in FIGURE 1 below. When the deviations were 2, the correlation factor was 0.98396, which does not meet the MEASNET requirement of 0.99994. The iterations were repeated multiple times until the value required could be met. The standard deviation of the results should also be less than or equal to 0.03 m/s

Table 1: Generated simulated results

Base Velocity(m/s)	Deviation 2	Deviation 1	Deviation 0.5	Deviation 0.12
4	3.331	4.496	3.966	4.002
5	5.204	4.578	5.205	4.988
6	5.526	5.943	5.841	5.949
7	7.308	6.607	6.882	6.969
8	8.378	8.462	7.823	7.955
9	9.496	8.505	8.818	8.962
10	9.901	10.275	10.185	9.969
11	10.168	11.317	11.040	10.990
12	11.458	12.369	12.025	11.946
13	13.827	12.584	12.822	13.048
14	13.305	13.900	14.177	14.053
15	15.652	14.760	15.061	14.999
16	16.077	16.300	15.925	15.999

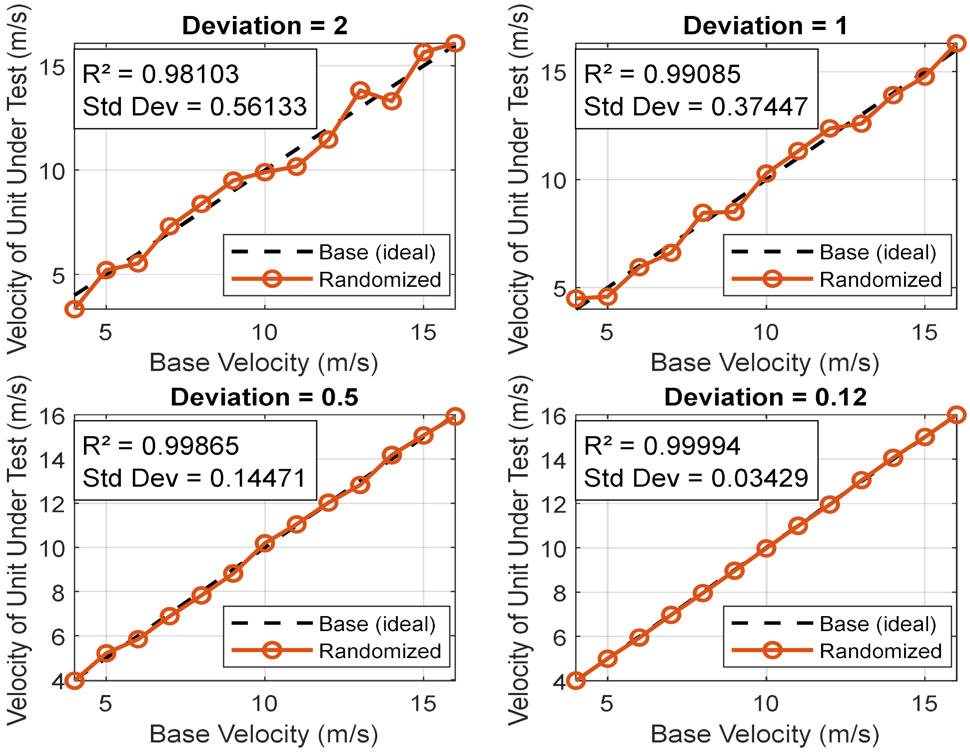

Figure 1: Plot of simulated results

Stability Analysis at Various Wind Speeds

The open jet wind tunnel is vulnerable to environmental changes. This has an impact on the stabilisation time, especially at low velocities. The developed MATLAB code was used to analyse the time required to acquire a valid point at various speeds starting at 4 m/s. The code takes an average of data points at different locations. This iteration is also repeated until the flow stability is achieved. This was conducted to determine if there are further modifications needed to be made to the wind tunnel. If the stability time of the data was greater than 20 or 30 minutes at a velocity lower than 8 m/s, it will mean that it will take the whole day to calibrate one cup anemometer.

Figure 3 and Figure 4 show the results obtained using 10 averages at a segment length of 50 seconds. This does not meet the MEASNET specification for the deviation of 0.12 m/s shown in Table 1. The results shown in Table 2 indicate that averaged data points should be recorded of over 500 seconds to get a stable and reliable value at 4 m/s. The deviation between minimum and maximum values in Table 2 and Figure 2 is 0.015 m/s which meet the MEASNET flow correlation factor requirement of 0.99994. Figure 3 and Figure 4 deviation is 0.4 m/s which does not meet the MEASNET requirement. The process was repeated for 8 m/s, and the time required to get reliable data came down to 5 minutes, and at 10 m/s upward, 2 minutes were used for acquiring intervals.

Table 2: Random averages for randomized length segments computed for 4 m/s data points over 500 seconds

Segment No.	Randomised average velocities
1	4.2338
2	4.0484
3	4.2239
4	4.1820
5	4.1995
6	4.0670
7	4.0245
8	4.1152
9	4.2365
10	4.1780

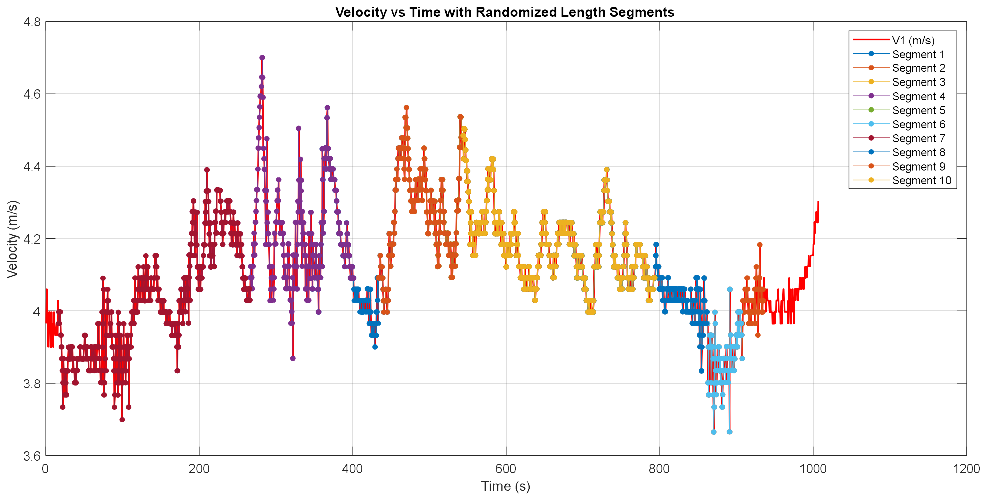

Figure 2: velocity vs time with randomized segments at 4 m/s

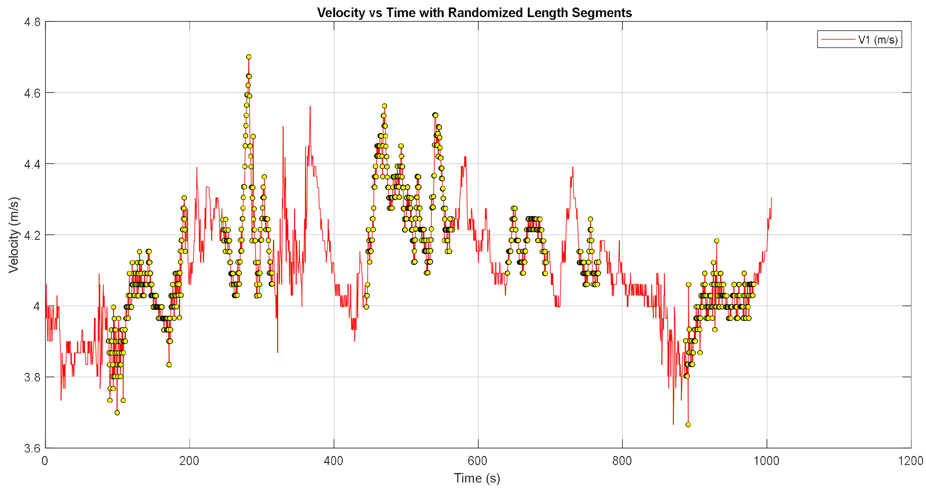

Figure 3: Velocity segments length with 10 computed measurements and 5 averages at 4 m/s

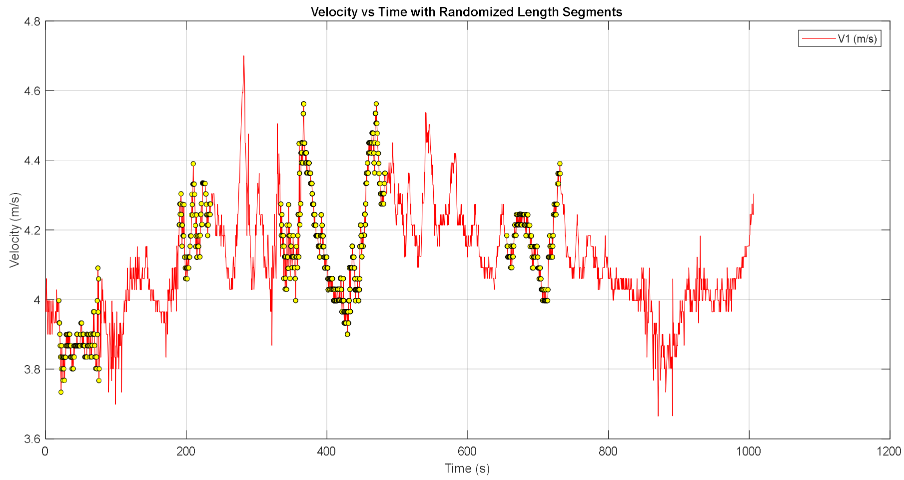

Figure 4: Velocity segments length with 10 computed measurements and 5 averages at 4m/s

Cup Anemometer Calibration Results Analysis

Two cup anemometers namely, Riso P2546A and Thies 4.3351.10.000 were calibrated using segment length of 500 seconds. The results are shown in Table 3 and Table 4 with their plot in Figure 5 and Figure 6, respectively. The calibration coefficients for both cup anemometers meet the MEASNET requirement. This shows that the open jet 2-mWT is suitable for the comparison against other international laboratories that are part of the MEASNET scheme.

Table 3: Results for Riso P2546A cup anemometer

No.	Sensor Output (Hz)	True Airspeed (m/s)	Uncertainty (m/s)
1	6.138	4.110	0.15
2	9.825	6.396	0.15
3	13.050	8.473	0.15
4	16.950	10.903	0.15
5	20.390	13.096	0.15
6	23.582	15.132	0.15
7	27.074	17.349	0.15
8	25.250	16.127	0.15
9	22.020	14.170	0.15
10	18.506	11.921	0.15
11	14.983	9.708	0.15
12	11.607	7.466	0.15
13	7.825	5.141	0.15

Table 4: Results for 4.3351.10.000 cup anemometer

No.	Sensor Output (Hz)	True Airspeed (m/s)	Uncertainty (m/s)
1	84.757	4.209	0.15
2	129.937	6.262	0.15
3	179.080	8.540	0.15
4	229.790	10.868	0.15
5	274.793	12.940	0.15
6	320.440	15.046	0.15
7	365.833	17.139	0.15
8	342.233	16.052	0.15
9	297.757	13.986	0.15
10	251.060	11.827	0.15
11	201.180	9.588	0.15
12	151.908	7.322	0.15
13	105.373	5.072	0.15

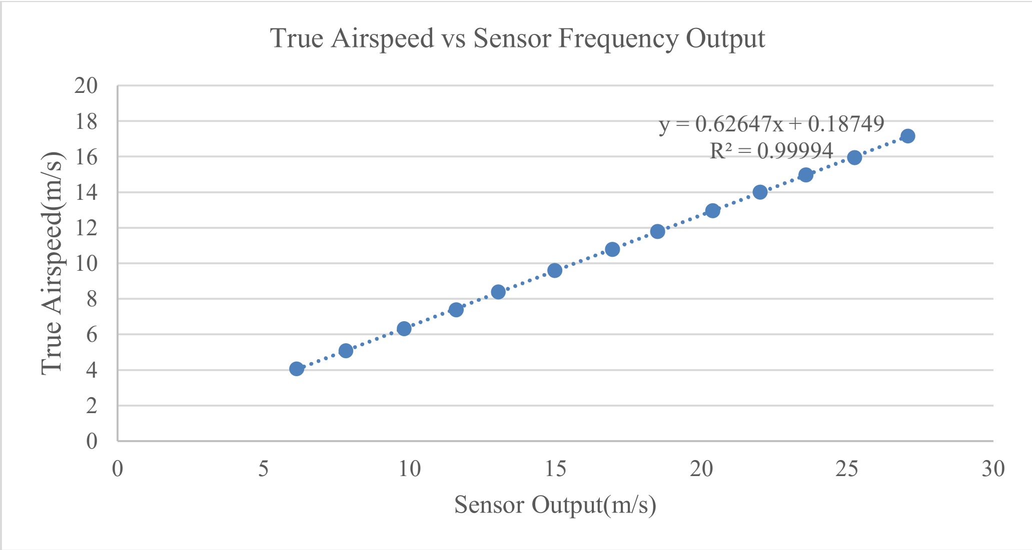

Figure 5: Riso P2546A True airspeed vs Sensor output

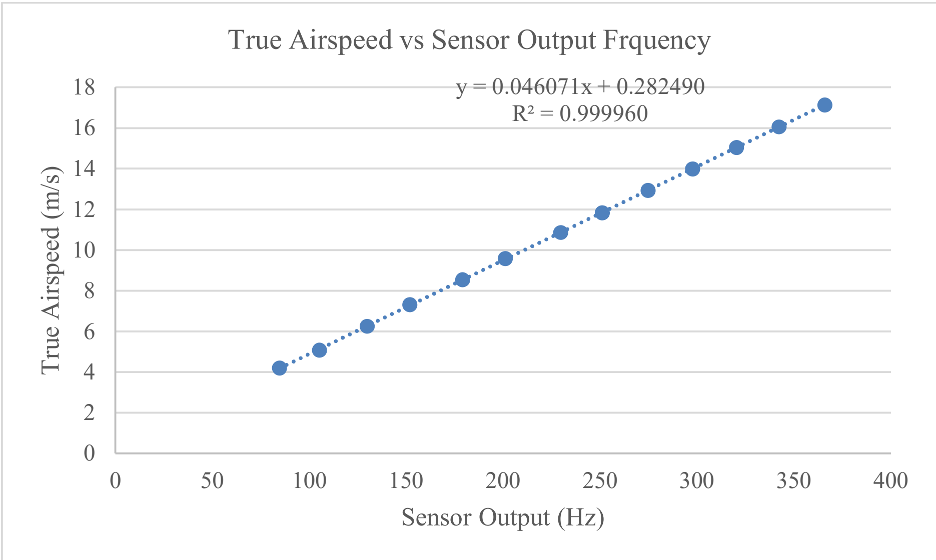

Figure 6: Thies 4.3351.10.000 True airspeed vs Frequency output

V. Discussion

The characterization of CSIR's 2mWT demonstrates promising alignment with MEASNET calibration standards, especially regarding flow uniformity and turbulence management. The analysis of deviation factors indicated that to achieve a correlation coefficient of 0.99994, it is crucial to control velocity deviations precisely, keeping tolerances under 0.12 m/s and standard deviations below 0.03 m/s. These results highlight the need for ongoing calibration and real-time data checks to meet international standards.

The stability assessment also pointed out how sensitive the open-jet setup is to environmental changes, particularly at lower wind speeds. The stabilization times varied quite a bit within the 4 – 16 m/s range, implying that we might need to implement extra flow conditioning or make changes to the enclosure to minimize outside interference. Even with these challenges, the tunnel performed reliably at mid-to-high wind speeds, confirming its capability for MEASNET compliant calibration.

Using a calibrated pitot tube as a reference standard, along with multi-point pressure readings and MATLAB-based analysis, created a solid framework for assessing flow characteristics. Comparing this with historical proficiency testing data from 2016 and 2024 validated the reliability of the setup and the accuracy of the cup anemometer measurements.

VI. Conclusion

This study successfully characterized the CSIR's 2mWT for potential MEASNET-compliant calibration of cup anemometers. Through iterative testing and flow conditioning, the CSIR 2mWT tunnel achieved:

- **Velocity deviations within ± 0.12 m/s**
- **Standard deviation of 0.03 m/s**
- **A correlation coefficient approaching the MEASNET requirement of 0.99994**
- **Stable and repeatable calibration results across the 4–16 m/s range**

The use of calibrated pitot tubes, environmental monitoring instruments, and MATLAB-based analysis provided a robust framework for evaluating flow uniformity and calibration repeatability. These results confirm the tunnel's technical viability for high-precision wind speed measurement.

Significance for the Africa Wind Energy Sector

Africa currently lacks a MEASNET-accredited facility for cup anemometer calibration, forcing developers to rely on costly and time-consuming overseas laboratories. The successful characterization of CSIR's 2mWT marks a pivotal step toward establishing a local, traceable, and internationally recognized calibration capability. This would:

- Reduce operational costs for wind energy developers
- Accelerate project timelines
- Strengthening regional expertise in wind measurement and instrumentation
- Position South Africa as a leader in wind energy metrology on the continent

Future Work and Recommendations

To build on the outcomes of this study, the following actions are recommended:

- **Infrastructure Enhancements**: Introduce flow conditioning elements to improve stability at low wind speeds.
- **Automation**: Develop automated calibration rigs to improve throughput and reduce human error.
- **Extended Calibration Range**: Expand the velocity range beyond 16 m/s to accommodate next-generation turbine technologies.
- **Accreditation Pathway**: Initiate formal steps toward MEASNET membership.

These efforts will not only elevate CSIR's wind tunnel capabilities but also contribute meaningfully to the growth and independence of Africa's wind energy infrastructure.

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