IEA Wind Task 46

Erosion of wind turbine blades

Test aluminum data analysis, damage accumulation and VN curves

Technical report

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iea wind

Technical Report

Test aluminum data analysis, damage accumulation and VN curves

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Purpose

Leading edge erosion (LEE) of wind turbine blades has been identified as a major factor in decreased wind turbine blade lifetimes and energy output over time. Accordingly, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) has created the Task 46 to undertake cooperative research in the key topic of blade erosion. Participatns in the task are given in Table 1.

The Task 46 under IEA Wind TCP is designed to improve understanding of the drivers of LEE, the geospatial and temporal variability in erosive events; the impact of LEE on the performance of wind plants and the cost/benefit of proposed mitigation strategies. Furthermore Task 46 seeks to increase the knowledge about erosion mechanics and the material properties at different scales, which drive the observable erosion resistance. Finally, the Task aims to identify the laboratory test setups which reproduce faithfully the failure modes observed in the field in the different protective solutions.

This report is a product of Work Package 4 Laboratory testing of erosion.

The objectives of the work summarized in this report are to:

- Present an analysis of rain erosion testing (RET) calibration, focusing on the comparison between three separate RETs of the R&D design. The study evaluates aluminum standards within the RET framework, examining tests conducted on 3003 and 3103 alloys.

Table 1 IEA Wind Task 46 Participants.

Country	**Contracting Party**	**Active Organizations**
Belgium	The Federal Public Service of Economy, SMEs, Self-Employed and Energy	Engie
Canada	Natural Resources Canada	WEICan
Denmark	Danish Energy Agency	DTU (OA), Hempel, Ørsted A/S, PowerCurve, Siemens Gamesa Renewable Energy
Finland	Business Finland	VTT
Germany	Federal Ministry for Economic Affairs and Energy	Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy SE, RWE, DNV, Mankiewicz, Henkel
Ireland	Sustainable Energy Authority of Ireland	South East Technology University, University of Galway, University of Limerick
Japan	New Energy and Industrial Technology Development Organization	AIST, Asahi Rubber Inc., Osaka University, Tokyo Gas Co.
Netherlands	Netherlands Enterprise Agency	TU Delft, TNO
Norway	Norwegian Water Resources and Energy Directorate	Equinor, University of Bergen, Statkraft
Spain	CIEMAT	CENER, Aerox, CEU Cardenal Herrera University, Nordex Energy Spain
United Kingdom	Offshore Renewable Energy Catapult	ORE Catapult, University of Bristol, Lancaster University, Imperial College London, Ilosta, Vestas
United States	U. S. Department of Energy	Cornell University, Sandia National Laboratories, 3M

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Executive Summary

The motivation behind this work stems from the increased adoption of Rain Erosion Testers among operators. The Recommended Practice 0171 includes a small round-robin comparison conducted in 2018 when the practice was first established. However, since then, our ability to analyze data has significantly improved. As part of the IEA Task, we have decided to collaborate among members to compare calibration specimens more comprehensively.

This study highlights the variability in RET calibration results across different test setups. By leveraging DTU-RETINA for systematic annotation, the study ensures accurate tracking of incubation onset and damage progression. The analysis of velocity and impingement relationships, supported by confidence intervals, provides insights into the erosion process.

1 Introduction

This report presents an analysis of rain erosion testing (RET) calibration, focusing on the comparison between three separate RETs of the R&D design. The study evaluates aluminum standards within the RET framework, examining tests conducted on 3003 and 3103 alloys. The coefficient of variation (COV) is assessed in accordance with DNV-GL 0171 standards, with a particular emphasis on velocity and impingement variations.

The motivation behind this work stems from the increased adoption of Rain Erosion Testers among operators. The Recommended Practice 0171 includes a small round-robin comparison conducted in 2018 when the practice was first established. However, since then, our ability to analyze data has significantly improved. As part of the IEA Task, we have decided to collaborate among members to compare calibration specimens more comprehensively.

An interesting aspect of this study is the evolution of annotation methods. Unlike previous approaches that fixed time steps at even intervals, we now allow for varying time steps, providing more flexibility and accuracy in analyzing erosion progression. Additionally, one dataset uses the older 3003 aluminum, originally specified in the Recommended Practice. However, this alloy is no longer produced in Europe, leading to a transition to 3103 aluminum. A key question has been whether 3103 aluminum is truly comparable to 3003 in erosion resistance. Addressing this uncertainty is an essential goal of this study.

Furthermore, the tests cover slightly different flow rates within the rain field, specifically at 160 and 165 L/h. While these variations exist, proper data treatment allows normalization, making meaningful comparisons possible.

2 Data annotation

Accurate annotation and data sharing are crucial for consistent analysis of RET calibration. DTU's in-house annotation tool, DTU-RETINA, provides a structured framework for tracking incubation points and test parameters. The tool ensures comprehensive documentation of test conditions, allowing for reliable comparisons across different RET setups. Screenshot of DTU's in-house annotation tool, DTU-RETINA, used for tracking incubation points and test parameters is shown in Figure 1.

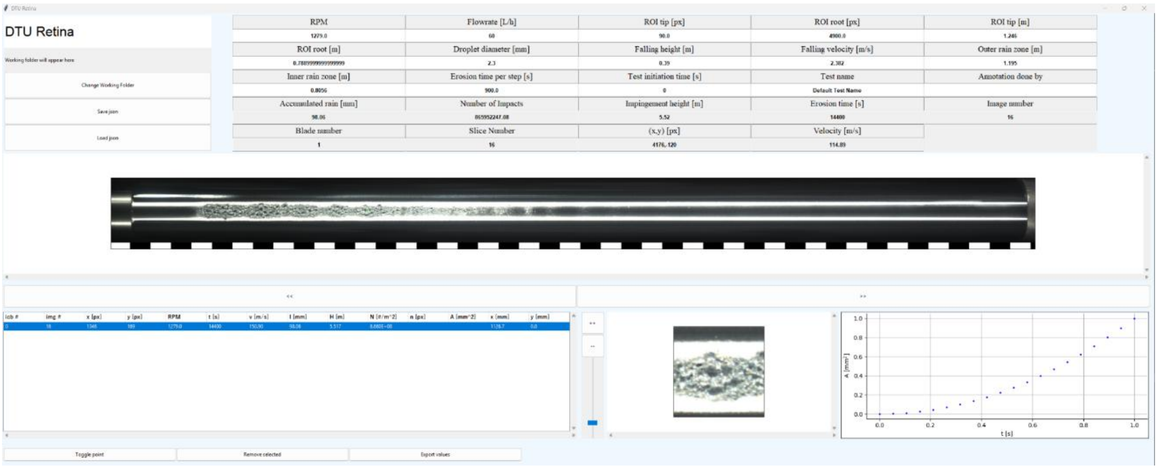

Figure 1: DTU-RETINA Annotation Tool.

3 Incubation determination

The onset of erosion is determined by detecting incubation points, which appear as localized pits or craters on the sample surface. Identifying these points is crucial in understanding when material degradation begins.

An essential part of this study involves refining damage detection methodologies. The figures in this report illustrate how the data is annotated using DTU's in-house tool, RETINA. Previously, damage detection relied on preset time steps, but in this analysis, a more dynamic approach is taken by allowing variable time steps, which improves tracking accuracy. The detected damages are characterized as small, individual pits that are separate from larger erosion areas. From prior experience, this method has proven to be the most repeatable metric when analyzing aluminum specimens, as these isolated pits are more distinct and less ambiguous compared to generalized erosion area, shown in Figure 2.

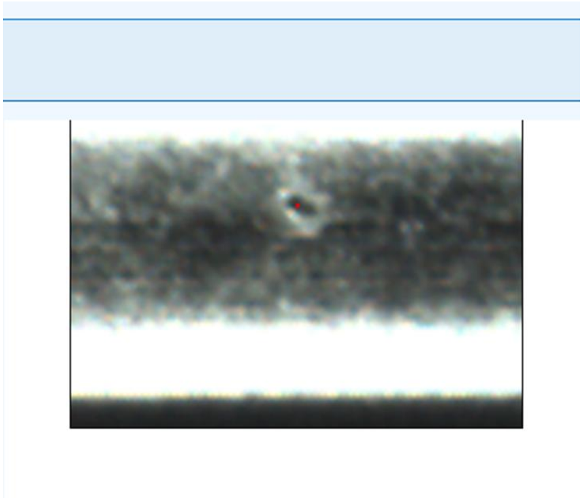

Figure 2: Identification of incubation onset.

A close-up view of an incubation pit, showing the initial signs of material degradation, see Figure 3.. These localized pits indicate the beginning of erosion and are systematically identified for tracking.

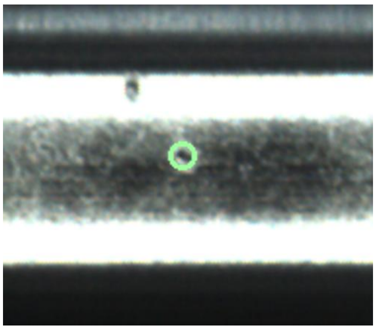

Figure 3: Incubation detection with 1.5mm radius circle.

To standardize the detection process, each identified incubation pit is marked with a 1.5 mm radius circle. This ensures consistency in damage assessment across different test setups, see Figure 4.

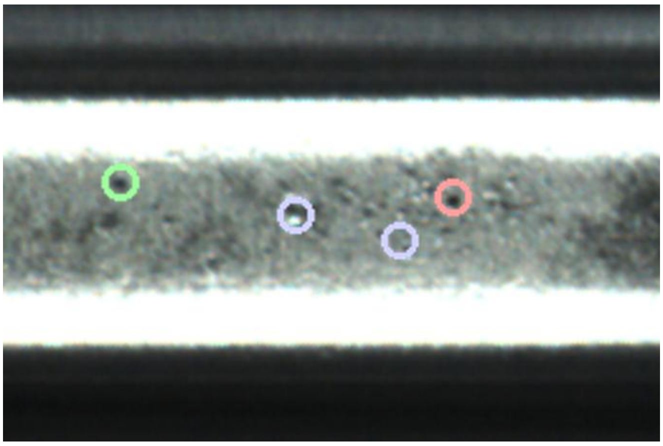

Figure 4: Tracking damage over time.

To analyze the evolution of damage, each time step is marked with a different color. Green circles indicate the current time step, red circles mark new damage, and purple circles represent damage from previous time steps. This tracking method allows us to assess damage accumulation over time.

4 Experimental Results

The following sections present the results of velocity versus impingement analysis, damage tracking, and coefficient of variation estimations. The data has been analyzed to assess the accuracy and variability of different RET setups A, B and C. The study includes 13 separate tests conducted across three different machines, with two different flow rates, two different materials, and varied reported droplet sizes, as summarized in Table 1.

A key objective of this study is to compare the calibration of different RET machines to ensure consistency across operators. The velocity vs. impingement relationship is a crucial metric, as it directly influences material erosion rates. By analyzing variations in velocity, we can determine how well different RET setups align with each other and assess the need for standardization. A key benefit of using aluminum specimens in comparative studies is that the erosion area can be allowed to progress for a longer duration compared to coated glass fiber composites. This extended progression enables incubation damage to develop over a wider speed range, improving annotation accuracy and data fitting. Even when tests are conducted exclusively under H-ALT (160 m/s tip speed) [3] conditions, the results still allow for robust VN curve fitting due to the extended observation window.

Another focus of this investigation is the impact of transitioning from 3003 aluminum to 3103 aluminum. Since 3003 aluminum was the reference material in the Recommended Practice DNV-GL RP 0171, but is no longer available in Europe, understanding the erosion behavior of 3103 aluminum is essential to ensure comparability in future tests.

Additionally, variations in flow rates within the rain field may affect impingement. This study considers flow rates of 60 L/h and 65 L/h. However, through appropriate data normalization, we can derive meaningful insights into how these variations influence the results.

4.1 Impacts per mm^2 comparison to DNV-GL RP 0171

The following section presents a comparison to the reference curves provided in the Recommended Practice DNV-GL RP 0171[1]. In the recommended practice, impacts per mm² are plotted against a reference curve, along with ±50% tolerance bands, as shown in Table 1.

It is important to note that n/mm² is not a proper rationalization according to ASTM G73-10, as it does not account for the affected area. Consequently, it is unsuitable for direct comparison between different tests and test setups. This metric is included here solely for reference to the data in DNV-GL RP 0171.

For all subsequent inter-test comparisons, the ASTM G73-10 compliant rationalization, impingement (H), will be used instead of n/mm² to ensure consistency and accuracy in data interpretation.

The table shows the data sets used in this study, from 3 different testers A,B,C and the reffence data from DNV-GL RP 0171 long with the substrate material, and fitted C and m parameters for the power curve.

Tester	**Run**	**Material**	**C**	**m**	**Droplet size [mm]**	**Fall velocity [m/s]**	**Flow rate**
Reference	Mean	3003	4.970985e+18	7.379	Assumed 2.4mm from DNV-GL RP 0171	Assumed 2.3m/s from DNV-GL RP 0171	60
	-50%		8.61e18	7.379			
	+50%		2.87e18	7.379			
A	1	3103	2.765471e+16	6.157855	2.32	2.35	60
	2		2.459115e+15	5.670409			
	3		3.667908e+14	5.256987			
	4		5.127435e+16	6.270723			
	5		4.548809e+16	6.27726			
B	1	3103	1.249092e+16	6.035431	2.221	2.333	65
	2		1.482544e+16	6.0999	2.276	2.428	
	3		2.739779e+15	5.632329	2.142	2.397	
	4		5.003032e+15	5.881307	2.298	2.4	
C	1	3103	3.232152e+14	5.254263	2.3	2.35	60
	2		1.901051e+13	4.691523			
	3	3003	5.902273e+12	4.429618			
	4		1.106065e+16	5.925293			

Table 1: Test data and fit with power fit in n/mm^2.

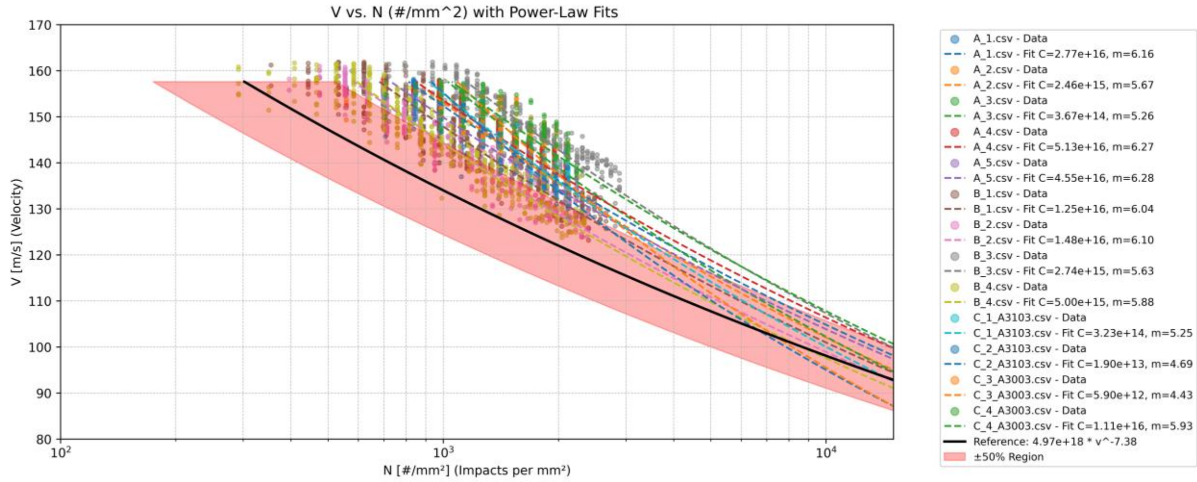

Figure 5: Velocity vs. impacts per mm².

This scatter plot in Figure 5 displays all annotated data points from the study, plotted and fitted to a power function. The fitted function is shown in the figure label. Additionally, the reference curve from DNV-GL RP 0171 is included, along with its ±50% tolerance band, providing a comparative framework for evaluation.

Keeping in mind that n/m^2 should not be used for comparision across tests that does now have 100% the same testing parametres, the initial impression from the data is that the testers in this comparision is on average less erosive for any given speed

4.2 Impingment normalized data

As mentioned in the section above, N/mm² is not a valid normalization according to ASTM G37-10 [2] when used on a distributed impact tester such as an R&D A/S-style whirling arm RET. Therefore, we will conduct the remaining part of the analysis using either impingement or the height of the impinged column of water.

To compare our results with the reference data in [1], we must convert from N/mm² to H(m). However, it is unclear from [1] whether the reference curve corresponds to a 2.4 mm or 2.5 mm diameter droplet size. To address this uncertainty, we will perform the analysis using a 2.45 mm droplet size.

$$N \rightarrow H$$

$$N(v)\left[\frac{n}{mm^2}\right] * 1e6 * volume\ of\ droplet[m^3]$$

$$H_{reffrence}(v)[m] = 4.970985e18 * v^{-7.379} * 1e6 * \frac{4}{3} * \pi * \left(\frac{0.00245}{2}\right)^3$$

The major benefit of using $H(t)$ is that it significantly reduces uncertainty related to droplet size. As shown in [5], impingement has been experimentally demonstrated to be the best simple normalization method.

The fundamentals of impingement are calculated as:

$$H(t) = \frac{I}{v_{droplet}} * v_{rotor}(r) * t$$

where I is the rain intensity in m/s, $v_{droplet}[m/s]$ is the fall velocity of the droplet, and $v_{rotor}(r)[m/s]$ is the tangential velocity at the point of impact on the rotor.

From this equation, we see that only the fall velocity is influenced by droplet size, and for most tests, this difference is small. The fall velocity is either measured directly or calculated using [1][2][3].

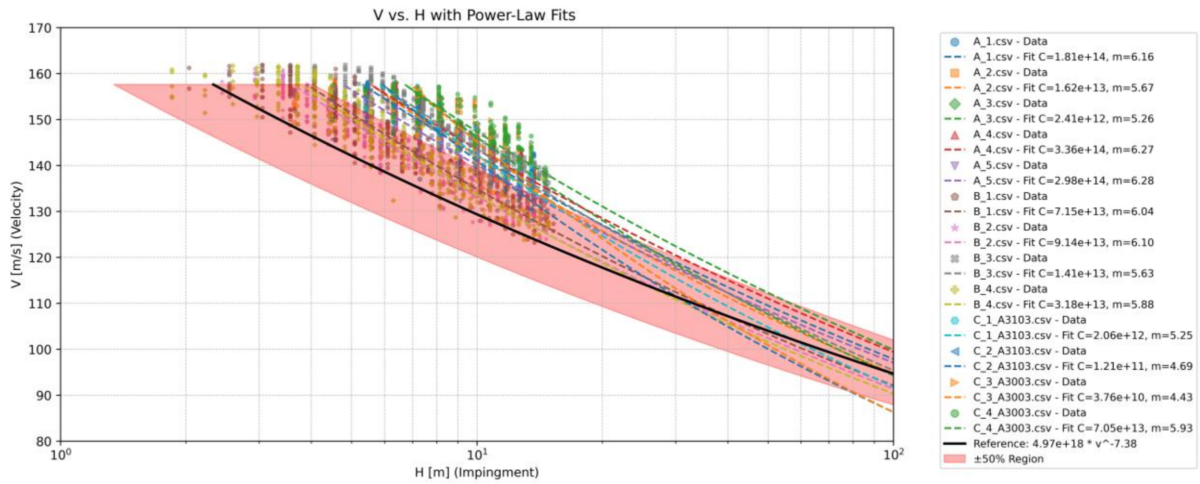

Figure 6: Velocity vs impingement with power fit.

Employing this approach, we obtain Figure 6. Comparing this to Figure 5, which is plotted on a similar scale, we see that more of the data falls within the original reference band. However, as expected, the results remain broadly similar since these tests were conducted under comparable conditions.

By examining the calculated COV% for all combined tests, as shown in Figures 7 and 8, we see that using impingement results in a slight reduction in the calculated COV%—from 21.63% when using impact per unit area to 20.98% for impingement.

Looking more closely, we observe that the data set B_3 moves closer into the cloud of points, suggesting that the assumed droplet size used in the impact per unit area calculation may have been slightly incorrect or the value used was out of calibration. In this case, this discrepancy results in a 0.65% reduction in COV%.

A key observation when comparing these results to [1] is that the RETs used in this study (A, B, and C) exhibit a ±20% COV, whereas the RETs in [1] showed a ±50% variation. All the RETs in this study belong to a newer generation that employs a slightly different blade attachment method, eliminating the bolts used in older designs. There are indications that this design change may have reduced turbulence during testing, which could be a contributing factor to the lower COV%.

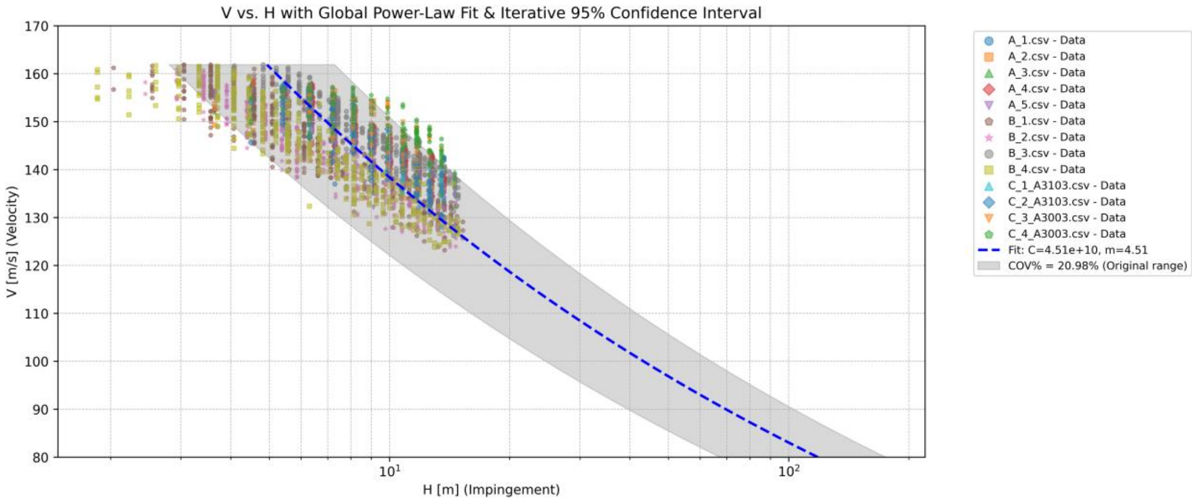

Figure 7: Velocity vs impingement with COV%.

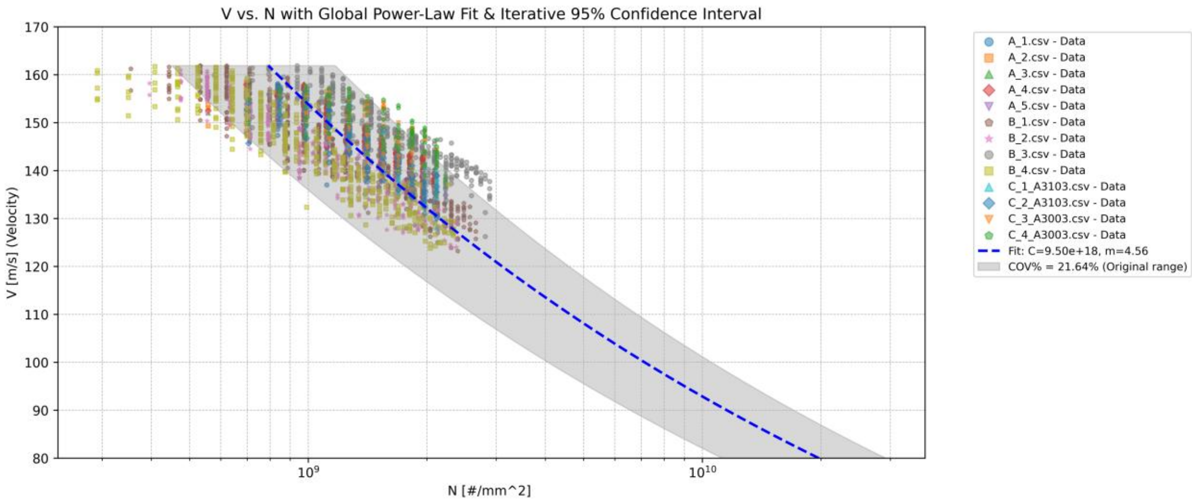

Figure 8: Velocity vs #/m^2 with COV%.

Individual results A B and C

The individual results from A, B, and C are shown in Figures 9, 10, and 11, along with the calculated COV%. We observe that all testers are at or below the 20% COV threshold, which is the general acceptance criterion when a RET is commissioned. Itis possible that the B_3 test is responsible for the increase to 20.22% COV.

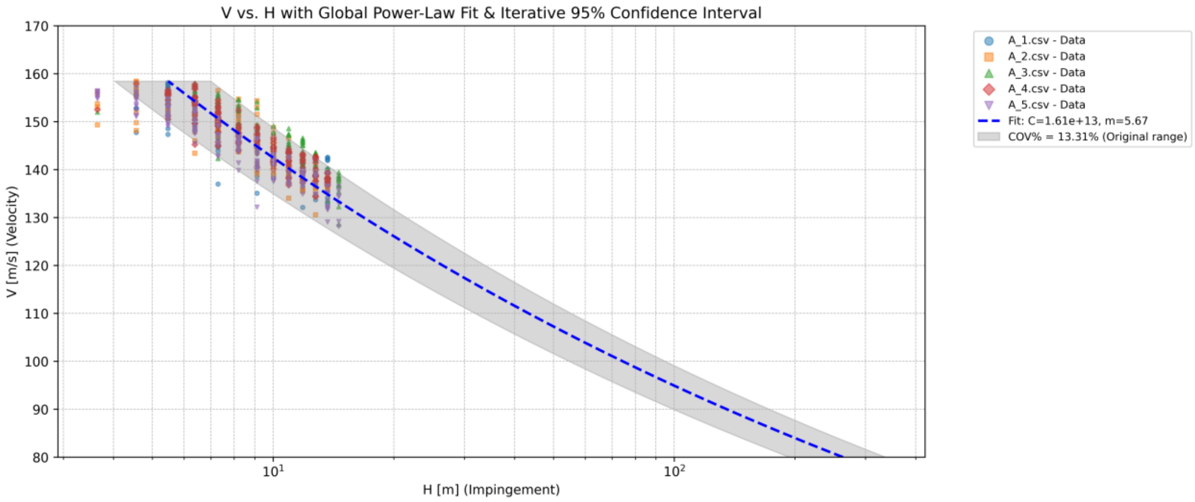

Figure 9: Velocity vs impingement tester A with COV%.

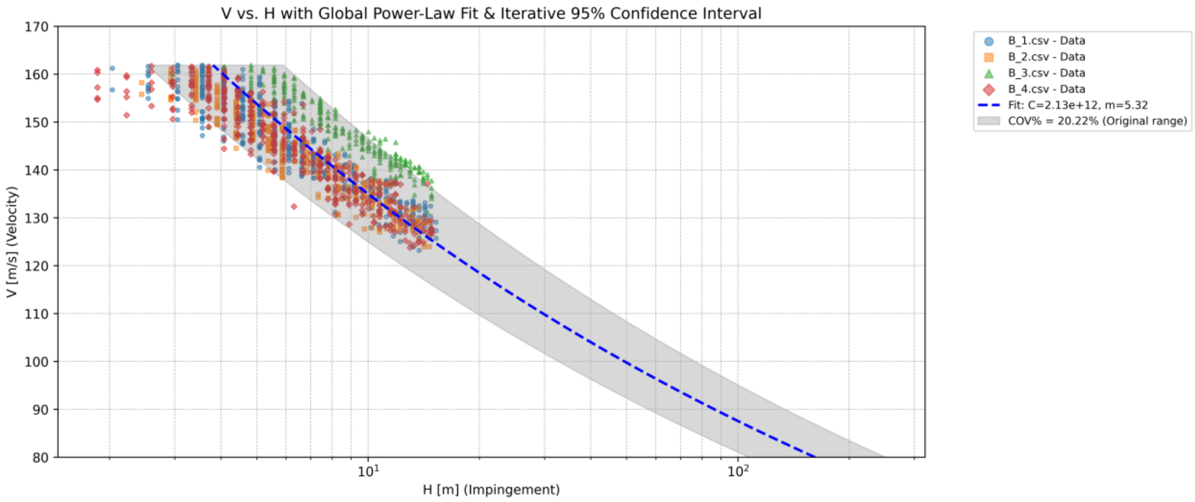

Figure 10: Velocity vs impingement tester B with COV%.

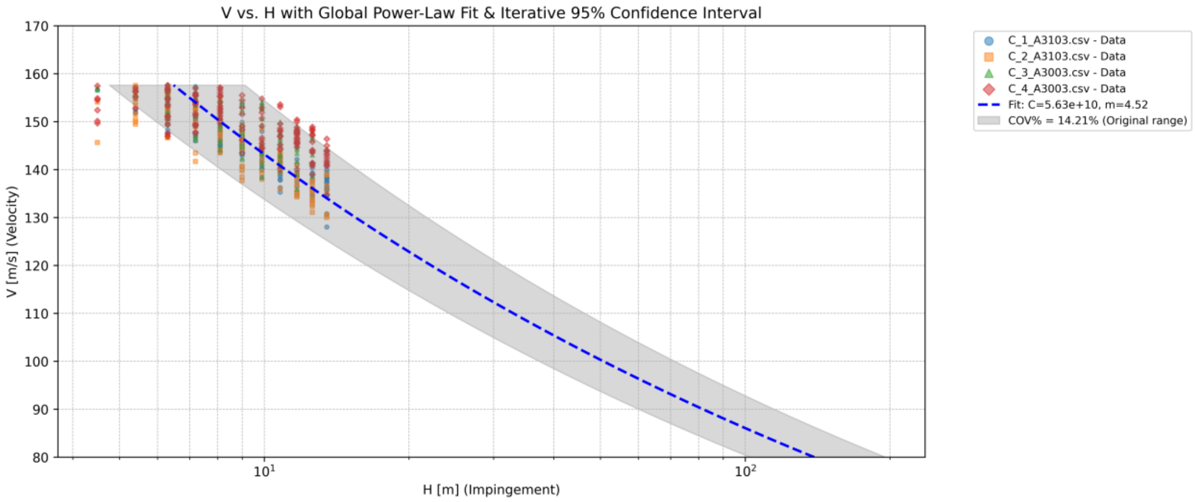

Figure 11: Velocity vs impingement tester C with COV%.

4.3 Effect of alluminium alloy on erosion performance

As mentioned, the original 3003 alloy used for the extruded profiles is no longer widely available, leading to a switch to 3103. A concern was whether this change would influence erosion performance and the quality of data from the RET, as we rely on calibration to provide a baseline indication of the inherent variance of the test.

From Figure 12, where both alloys are plotted together, we observe an acceptable **COV of 14.21%**. When analyzed separately, **3103 has a COV of 10.19%**, while **3003 has a COV of 16.55%**. However, with only two repetitions per material, it is unclear whether this difference is statistically significant.

There appears to be a trend suggesting that **3003 might have a slightly longer impingement-to-incubation period**, contradicting the hypothesis that the longer average incubation period observed in this study is due to the material change. Despite the small dataset, **3103 shows a slightly lower COV%**, though this might be attributed to poorer surface quality on the 3003 samples rather than differences in material properties, but as we rely on images alone for this study it is only an inference.

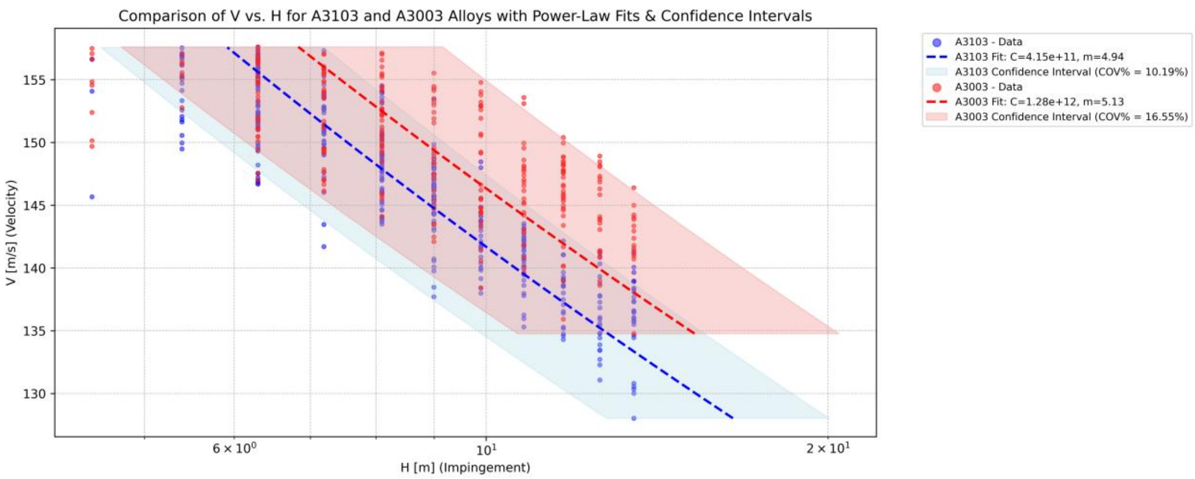

Figure 12: Velocity vs impingement for two alloys.

5 Conclusion

This study has provided a comprehensive analysis of **rain erosion tester (RET) calibration**, focusing on aluminum standards and the transition from **3003 to 3103 alloys**. The primary goal was to assess the impact of this material change on **erosion performance and data reliability** within the RET framework.

Key findings from this study include:

1. **Comparison of Normalization Methods:**
   - Traditional **impact per unit area (N/mm²)** normalization was found to introduce additional uncertainty due to droplet size variations.
   - **Impingement (H)** was confirmed as a more robust normalization method, reducing variability and improving consistency across tests.
2. **Coefficient of Variation (COV) Analysis:**
   - The overall **COV for all tests combined was 20%**, demonstrating an acceptable level of variability
3. **Material Influence on Erosion Performance:**
   - Data suggests that **3003 may have a slightly longer impingement-to-incubation period** compared to 3103.
   - The slightly higher COV% for 3003 could be attributed to **poorer surface quality**, rather than fundamental differences in erosion resistance, however more testing is needed.
   - When analyzed separately, **3103 exhibited a COV of 10.19%**, while **3003 had a higher COV of 16.55%**.
   - With only two repetitions per material, it remains **unclear whether this difference is statistically significant difference between 3003 and 3103**.
4. **Evolution of RET Calibration:**
   - The new generation of RETs used in this study demonstrated lower variability (±20% COV) compared to the **±50%** COV reported in **DNV-GL RP 0171**.
   - This may be linked to **improved blade attachment methods**, which eliminate bolts and potentially reduce turbulence effects.
5. **Annotation Method:**
   - The Annotation method seems repeatable across near identical test,
   - DTU-RETINA resulted in a simpler annotation process

Implications & Recommendations

- **Future RET calibration studies should prioritize impingement-based normalization** over N/mm² to enhance comparability across different test setups.

- **Additional repetitions of 3003 and 3103 tests** would help determine whether the observed COV differences are statistically significant.
- **Surface quality should be more rigorously controlled** to minimize potential artifacts affecting COV measurements.
- **Include Older RET's** to see if the new rotor design explains the difference.

Despite the **limited sample size**, this study provides **valuable insights into RET calibration and material performance**, ensuring improved data reliability for future wind turbine erosion assessments.

6 References

[1] DNV-GL. (2018). Recommended practice — DNVGL-RP-0171 (Issue February).

[2] ASTM. (2017). ASTM G73 - 10 (Reapproved 2017) Standard Test Method for Liquid Impingement Erosion Using Rotating Apparatus1. https://doi.org/10.1520/G0073-10R17

[3] DNV-GL. (2020). DNVGL-RP-0573: Evaluation of erosion and delamination for leading edge protection systems of rotor blades. December.

[4] DNV-GL. (2016). DNVGL-CP-0424 Type approval Coatings for protection of FRP structures with heavy rain erosion loads (Issue May).

[5] Bech, J. I., Johansen, N. F. J., Madsen, M. B., Hannesdóttir, Á., & Hasager, C. B. (2022). Experimental study on the effect of drop size in rain erosion test and on lifetime prediction of wind turbine blades. Renewable Energy, 197, 776–789. https://doi.org/10.1016/j.renene.2022.06.127