Final report

1.1 Project details

Project title	Rain Erosion Tester for accelerated test of wind turbine blades Regn erosions-tester for accelereret test af vindmølle-vinger
Project identification (program abbrev. and file)	**EUDP 2015-I, J.nr. 64015-0045**
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrations Program (EUDP)
Project managing company/institution (name and address)	R&D Test Systems A/S, Delta 4, 8382 Hinnerup, Denmark
Project partners	DTU Wind Energy
CVR (central business register)	37844179
Date for submission	29th June 2015 (date of funding approval received)
Date of final report	28th March 2018

1.2 Short description of project objective and results

The objective of this project is to develop a test machine, a rain erosion tester (RET), on which rain erosion of wind turbine blades can be simulated. RET can accelerated simulate erosion and exfoliation of the surface of wind turbine blades and thus avoid expensive repair and power loss for wind turbines and hereby lower the cost of energy. Project was executed by a consortium consisting of DTU and R&D Test Systems.

Result of the project is a test machine located at R&D's office in Hinnerup, Denmark. This machine has been running several thousand hours of test and has been recognised within the Wind Industry as the standard for rain erosion testing of wind turbine blades. 5 different customers within the Wind Industry has bought such a RET from R&D and 8 other customers are considering a RET purchase from R&D. A coming Recommended Practice from DNV-GL on how to test wind turbine blades for rain erosion is based on the R&D RET units.

DK: Projektets formål er at udvikle en Regn Erosions Testmaskine (RET), der kan simulere regn erosion på vindmølle vinger. Ved at udføre accelererede regn erosions test på vingemateriale-prøver, kan der udvikles vinge-materialer, der kan modstå det hårde slid fra regnvejr og dermed kan tab af elproduktion og dyre vingereparationer undgåes. Projektet blev udført af et konsortium bestående af DTU og R&D Test Systems.

Resultatet af projektet er en RET maskine, der er placeret ved R&D's hovedkontor i Hinnerup, DK. Maskinen har gennemført flere tusinde testtimer og er blevet anerkendt i Vind Industrien som standarden for, hvordan en regn erosions test udføres. Maskinen er allerede solgt i 5 eksemplarer til forskellige kunder i vind industrien og 8 andre kunder overvejer pt. at købe et sådant test anlæg hos R&D. DNV-GL er ved at udarbejde en Recommend Pratice for, hvordan regn erosions test skal udføres og den er baseret på R&D's RET maskiner.

1.3 Executive summary

The focus area of this project is wind energy and the reduction of the cost of energy for wind turbines.

The project deals with a costly problem within the wind energy sector – erosion of the wind turbine blades caused by rain. The erosion can lead to delamination of the surface of blades, which can cause a loss of aerodynamic efficiency – and furthermore significant costs to repair unforeseen damages. This problem typically appears sometime after erection of wind turbines. The consequences of erosion are significant as Sareen et al stated in their research article "Effects of leading edge erosion on wind turbine blade performance" in Wind Energy (2014). They note that "…small amount of leading edge erosion can result in an annual energy loss of approximately 3–5%" and that heavy erosion can cause a loss of up to 25%. According to an article in the magazine "Ingeniøren" of 8th of December 2013 (http://ing.dk/artikel/vingeforkanter-er-som-daekkene-paa-en-bil-164767) the problem is real and is especially critical for offshore sites.

The objective in this project is to develop state-of-the-art technology within rain erosion testing. The aim is that R&D wants to market a rain erosion tester, RET, which enables an accurate and repeatable simulation of erosion combined with valid data collection.

A RET provides an opportunity for the coating / blade / wind turbine manufacturers to test what surface that will provide the best endurance under rain exposure. This is very hard to perform theoretically and thereby the RET offers manufacturers a mean to identify and understand the risk of unexpected damages caused by erosion and thereby lower the cost of energy.

R&D has developed a basic RET, which can simulate erosion on test specimens. The RET consists of a rotating propeller with 3 test specimens being exposed to water drops coming from a rain generation system. This unit can perform tests comparable to the level of technology offered in the market of operating test centers.

For manufacturers etc. to understand the erosion via testing – and thereby minimize the cost of energy – it is the technical aim of this project to develop the technology to a state-of-the-art level. This will enable the customers to minimize erosion by:

1. Creating an accurate simulation of erosion with high repeatability.
2. Enabling valid collection of data by inline vision system and related data interpretation.

To achieve these technical aims an interdisciplinary effort was required combining aerodynamic analysis, high-level vision technology and structural design. Therefore, a partnership between R&D Test Systems and DTU was set up, where effort was put into developing a demonstrator.

The demonstrator was build and placed at R&D's head office in Hinnerup, Denmark. It has for now had several thousand test hours and demonstrated a high repeatability by having a COV < 10% at a developed calibration test method using aluminium test specimens and analysing mass loss.

Test result is documented by high quality photos of the test specimen during the test period, which is released in a fully automatic generated pdf report together with all other relevant test data (speed of rotor, water temperature, rain volume etc.). Photos is of such a quality that incubation period and breakthrough can be found directly by analysing the pdf report.

R&D A/S and DTU have together with key players in the wind energy sector made a successful proof of concept demonstrated by sales of 5 RET units to 5 different customers within the wind energy sector. The unit is market today by contacting relevant customers directly and already 8 other customers in the wind energy sector are considering a purchase of a RET unit.

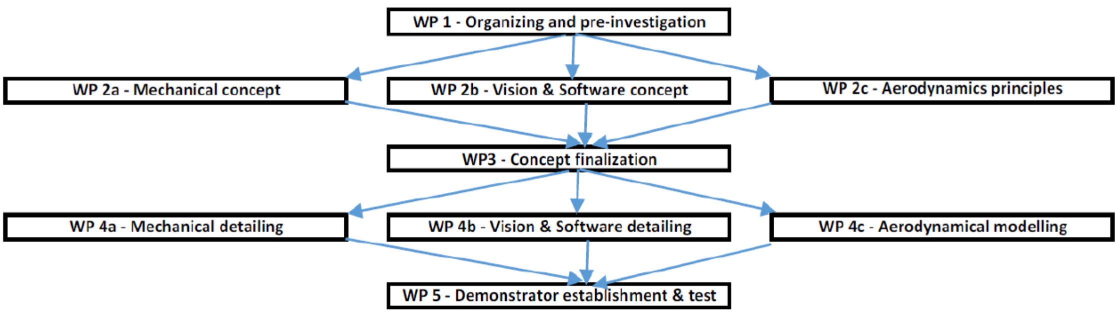
The overall goal is to enable a reduction in the operational expenditure for the wind energy sector and thereby lower the cost of energy. By using the R&D RET to test what surface can provide the best endurance under rain exposure the surface manufactures can easy and fast test their developments to get to successful surface solution for wind turbine blades. Wind turbine manufacturers can also use the RET unit to test which surface suppliers are the best to use when designing new turbine blades.

The distribution of the R&D RET unit demonstrates increased development activities in the wind energy sector to reduce the rain erosion issue on wind turbine blades.

1.4 Project objectives

The objective in this project is to develop state-of-the-art technology within rain erosion testing. The commercial aim is that R&D wants to market a rain erosion tester, RET, which enables an accurate and repeatable simulation of erosion combined with valid data collection.

Work in the project was organised by the following work packages:



Together with detailed plans for each work packages the organisation worked quite well to reach the state where a Test unit was assembled, run-in and calibrated.

During the first set of tests some experience was obtained and lead to further development of the different systems that the RET unit consist of. All in all, a constructive cooperation between DTU and R&D Test Systems developers.

1.5 Project results and dissemination of results

In the following the final design of the RET unit is presented together with selected results which lead to this final RET design. Some of the results are also used to improve the way rain erosion is characterized in general.

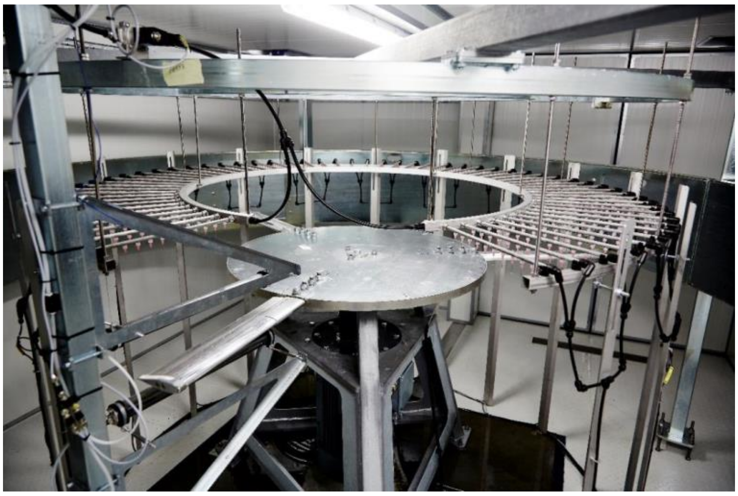
1.5.1 Rain Erosion Test unit - description and performance

The rain erosion demonstrator test unit (RET) was built at R&D's head office in Hinnerup, DK and is still placed at this site. In figure 1 photos of the unit are shown. Many details in the RET unit is based on the knowledge described in the previous sections.

The R&D RET unit consist of the following systems:

- Water system to produce demineralised water for the rain system
- Rain system with 600 needles to create the artificial rainfall
- Rotor with 3 blades/arms to hold and rotate the test specimen at high speed
- Ventilation system to ensure humidity level in the test container is kept at an acceptable level for the equipment to function
- Vision / camera system to capture the erosion development of the test specimens
- Electrical system to supply components with power and to control all systems enabling full automatic operation of the unit in a safe way

All of this is installed in 2 container cabinets – test unit is separated from operator unit for safety reasons.



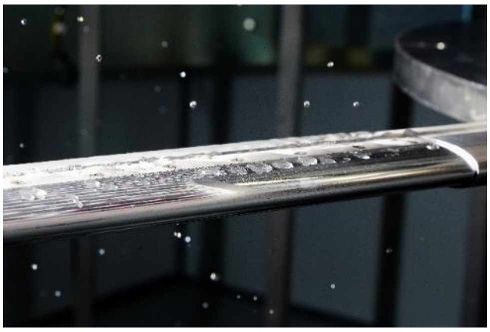


Figure 1: R&D RET unit placed at R&D's head office in Hinnerup, Denmark.
Test unit is placed in a double container safely closed during test. The second container is housing the operator control unit, electric installations and water treatment unit. Close-up photo shows a test specimen in the artificial rain field produced in the test unit.

Overall performance of the unit is as follow allowing the test performer to vary the most important parameters influencing the character of rain erosion:

- Tip speed from 63-173 m/s (500-1386 RPM)
- Rainfall 60-120 l/h (29-56 mm/h)
- Controlled water inlet temperature (4-30 deg.)
- Stable rain field with uniform droplets (diam. 2,0 – 3,5 mm)
- Controlled air exchange
- Test duration (slice time and number)
- Falling height 200-400 mm
- Test specimen exposure length up to 350 mm
- Quick shift specimen holder
- **COV < 10%** at a developed calibration test method using aluminium test specimens and analysing mass loss.

Calibration result from the Factory Acceptance Test is shown below here:

Cal. set	Wing 1 [g]	Wing 2 [g]	Wing 3 [g]
1st	2.1720	2.3800	2.2567
2nd	2.5097	2.6427	2.5207
3rd	2.2247	2.3403	2.2907
4th	2.4097	2.5130	2.6433
5th	2.3120	2.3177	2.1533
6th	2.3363	2.5893	2.3033
7th	2.0613	2.2910	2.1620
8th	2.1453	2.5410	2.2410

Table 2: Obtained mass losses of each wing after eight hours of test

The obtained CoV for the FAT calibrations is found to

$$CoV_{FAT} = 7.05\,\%$$

Ref.: R&D Rain Erosion Tester, Calibration Sheet. Calibration Procedure and Results, 18.09.2017 Rasmus B. Andersen

Similar tests have been performed at the other delivered RET units and all have a COV < 10%. This document that the RET unit has a very high repeatability of rain erosion tests.

The vision system to document the test results is an in-line system, where camera with lens is in a fixed position in front of where the test specimen is positioned when rotor is stopped for photo shooting. See figure 2 for illustration of this.

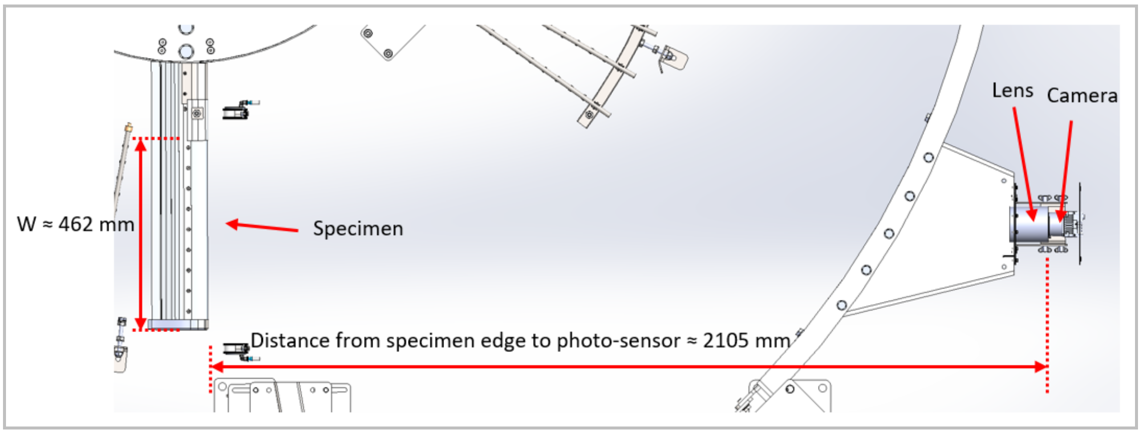


Figure 2: R&D RET unit in-line vision system. Positioning of camera relative to the rotor with test specimen

Examples of the test photos (aluminium test specimen) is shown below here in figure 3. Photo is of such high quality that you easily can detect the incubation and follow the erosion front and breakthrough on the test specimen during test.

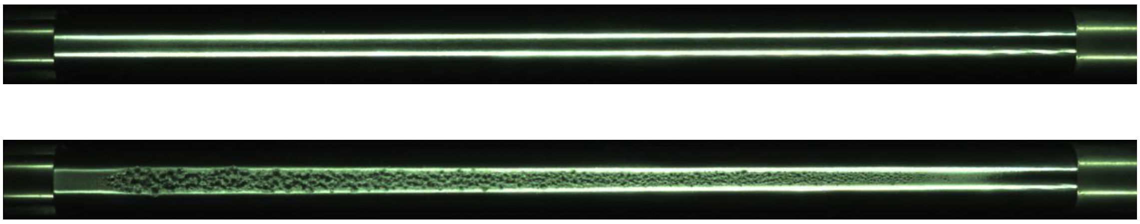


Figure 3: R&D RET unit test specimen photos (1. Test start, 2. Test completion). Test specimens shown is made os aluminium, which is why the erosion occurs as small round holes.

1.5.2 Single Point Impact Fatigue Tester (SPIFT)

In the project a single point impact fatigue tester (SPIFT) was developed at DTU as a supplement to the RET to generate impact fatigue damage and SN data, see Figure 4. Rubber balls are repeatedly impacted on a single location of the coated laminate. Each impact induces transient stresses in the coated laminate. After repeated impacts, these stresses generate cracks, leading to the removal of the coating and damage to the laminate. High-resolution digital imaging is used to determine the incubation time until the onset of coating damage. An acoustic emission sensor placed at the back of the laminate monitors changes in acoustic response as damage develops in the coated laminate. The subsurface cracks are studied and mapped by 3D X-ray computed tomography. A finite element method model of the impact shows the impact stresses in the coating and the laminate. The stresses seen in the model are compared to cracks found by 3D X-ray computed tomography. The damage is also evaluated by ultrasonic scanning.

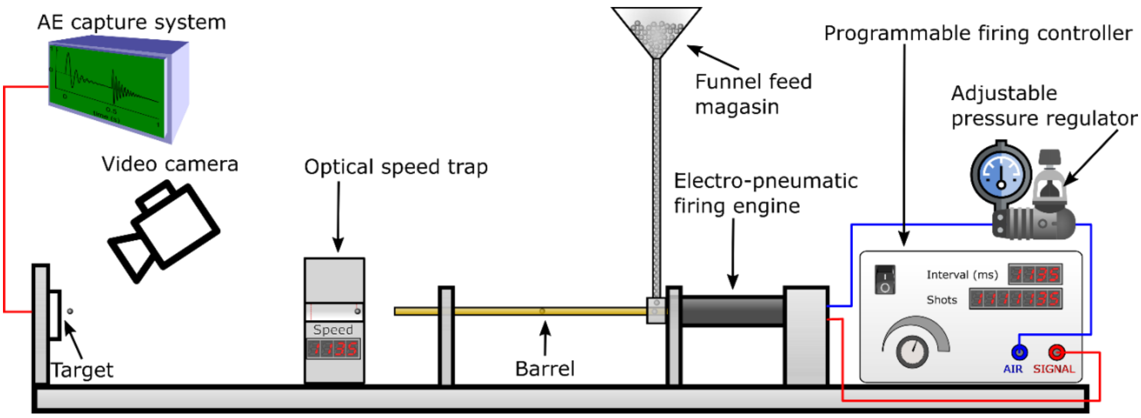


Figure 4: Schematic diagram of the single impact fatigue tester (SPIFT). "AE capture system" is the acoustic emission sensor.

1.5.3 *Characterization of RET and SPIFT samples by electron microscopy and X-ray tomography*

RET samples tested to failure were investigated by electron microscopy at locations with surface erosion, close to areas with surface erosion and very far from the eroded area. In all three cases, cracks were found at the peel-ply interface and at the outermost interface of the laminate.

The top coating was found to contain flaky particles consisting of a compound of Si, Al and K. Cracks were seen to develop at the flaky particles close to eroded areas, figure 5a, and evidence of degradation by spalling from the flaky particles were found. The top coating was observed to have a high porosity and microscopic cracks was found connecting the holes in the porous structure.

A black interface was observed through the whole sample in both the top coating and the filler, indicating that they have been applied as several layers. The black line in the filler was observed to have a porous structure most likely caused by microscopic bubbles.
SPIFT samples tested to failure had cracks close to the degraded area that were pointing directly into the top coating and no cracks at the flaky particles in the top coating, figure 5b. In the SPIFT sample tested with 100 impacts at 150 m/s no visual damage was observed on the surface but a crack was observed by X-ray tomography below the surface at the location of the black interface line in the filler, Figure 5c.

Based on the observations it is concluded that the RET and SPIFTS tests seem to activate different damage mechanisms in the samples. However, future work will investigate the two methods further.

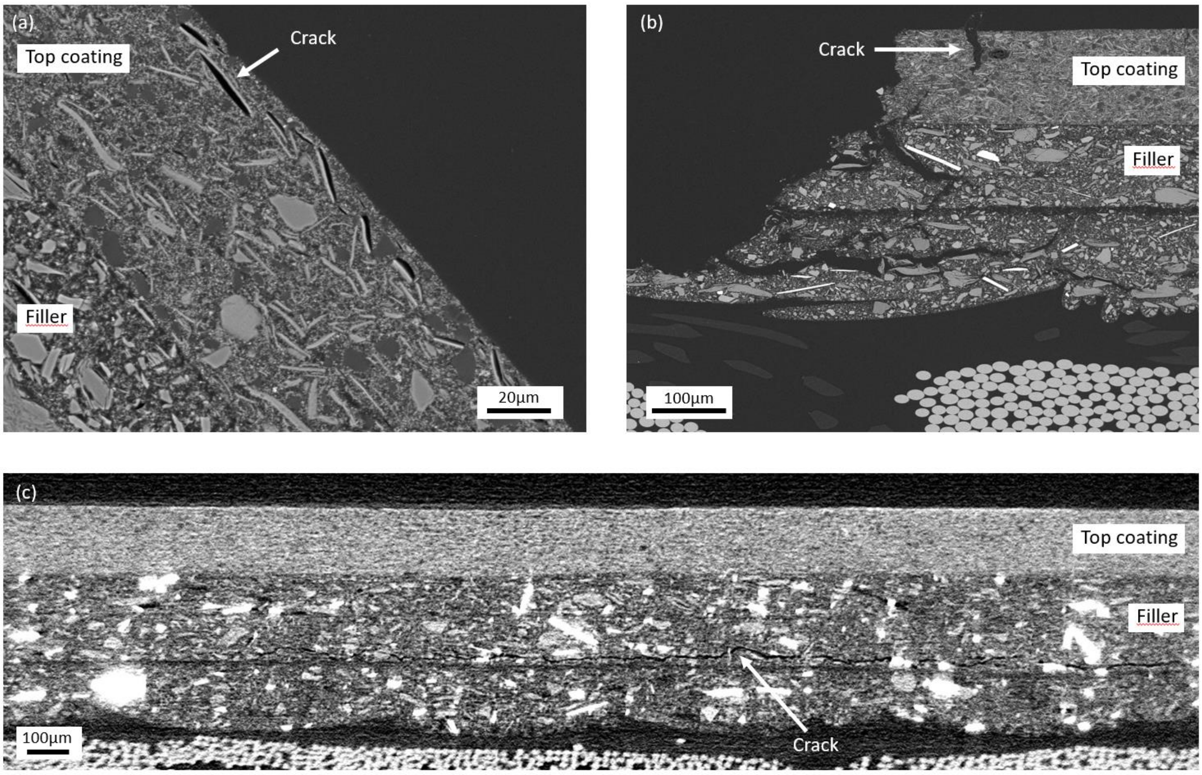


Figure 5: (a) Scanning electron microscopy (SEM) image of a cross section through a tested RET sample. Cracks (black) are located close to long flaky particles (bright). (b) SEM of a cross section through a SPIFT sample. Cracks at the surface are pointing directly into the top coating. (c) A virtual section through a tomographic reconstruction of a tested SPIFT sample with no visual damage. A crack is observed in the filler close to the black interface line.

1.5.4 SN or life time curves from RET results

RET specimens delivered by R&D to DTU were tested at the Rain Erosion Test facility at R&D A/S. The specimens are manufactured by Olsen Wings to meet the dimensions specified by R&D A/S.

The specimens are made from glass fiber reinforced epoxy. A layer of putty/filler was applied to the specimens and later a paint was spray coated on the specimens.
The tests were performed at 2 different droplet sizes (2.4mm and 3.5mm) and 3 different rotor velocities (1065 RPM, 1193 RPM and 1350 RPM).

Figure 6 left shows one of the 3 blades at the test condition 1193 RPM, 2.4 mm droplets and rain intensity of 29 mm/hr

Figure 6 right shows the accumulated rain to failure as a function of the local rotor tangential velocity for 2.4 and 3.5 mm droplets. It is seen, that the SN curve for 2.4 mm drops has a lover slope than the curve from 3.5 mm drops.

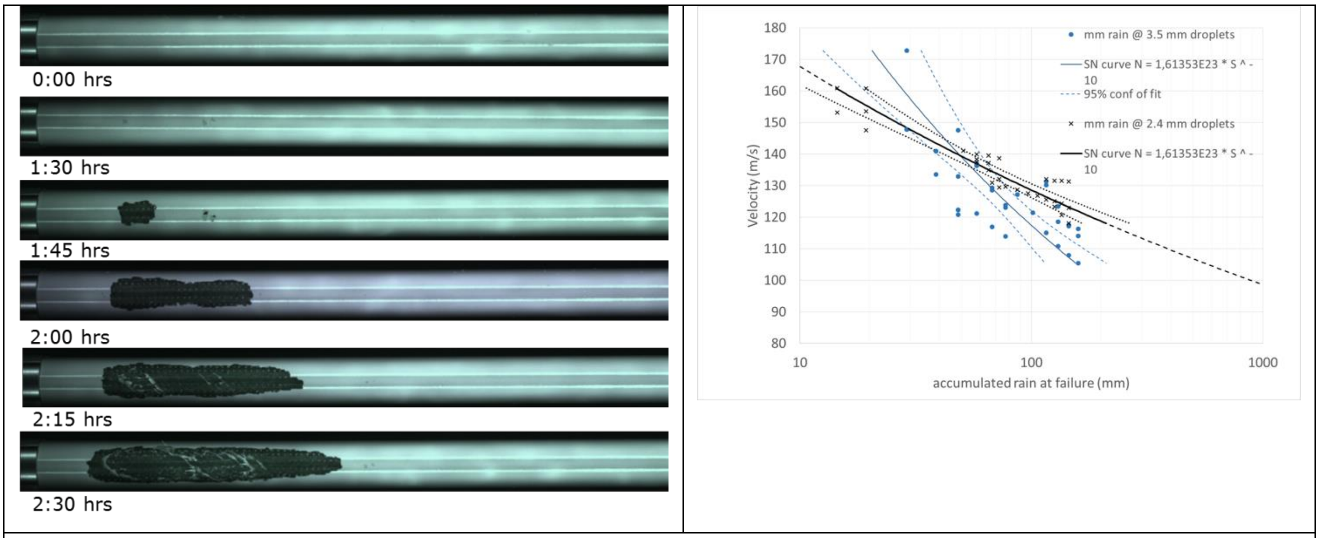


Figure 6: Left: example of a damage development with 2.4mm droplets and 1193 RPM. Right: S-N curve for RET tests and SPIFT tests on the same type of laminate.

1.5.5 TUFT Tests

At the outset of the project the expectations were that the spinning centre metal disc and the three blades would create a relatively large rotating disc of air around the rotor plane, including both tangential and radial flow components.
The initial CFD simulations showed that this was not the case but the disturbances were confined to a very small disc close to the blades.

To validate the findings from the simulations a small test campaign was performed at LM Wind Power's RET. The idea was to visualise the flow movements with tufts (small yarn threads and follow the air) mounted above the rotor plane and then record if they started moving when the RET was spinning. Some pictures of the setup are shown in Figure 77.

Basically, the small investigation confirmed the findings from CFD, i.e. that the flow is only disturbed in a very thin layer (approximately 5 to 10 cm above the blades) close to the rotor plane.

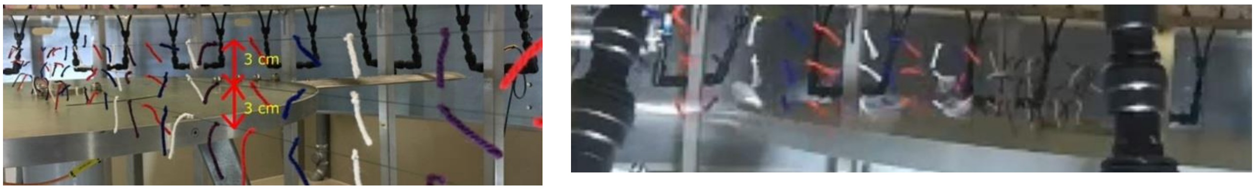


Figure 7: Left picture shows the tuft at standstill and right picture shoes the tuft at 700 RPM and no rain. Only the lowest row of tufts (approximately 5 cm above the blade) is moving significantly

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1.5.6 High Speed Camera Tests

Since the droplet relative speed and size at impact is of key importance to the erosion process, it is important to know how these are affected by the complex flow disturbances stemming from the rain erosion tester itself. This is investigated in the present work using high speed camera recordings and CFD.

Based on the results of the present work the following conclusions can be drawn (Figure8 shows an example of the obtained results):

- Results from the high-speed video of the RET shows that the droplets do not break up before they impact on the blades

- A droplet trajectory simulation method was described. The method is based on a combination of Newton’s second law with an engineering approximation for the aerodynamic drag of a sphere.

- The droplet trajectory algorithm was used with the time-varying velocity fields from CFD calculations to obtain simulated droplet trajectories.

- The simulated and measured droplet trajectories are in fair agreement with the computational counterpart based on CFD computations, which show that even for a rotor tip speed of 170m/s, the deflection of the droplets relative to the undisturbed path is relatively small (measurements: below 0.05m in all cases/ CFD: below 0.02m in all cases).

- An investigation using CFD of the effect of changes in flow field and droplet trajectory due to a pitch angle of the blades on the RET rotor show that nose-down pitch change of two degrees will induce large (7 m/s) upward velocities at radial positions corresponding to mid-span of the blades, which can result in larger changes in the droplet trajectories and impact positions of the droplets at mid-span. This indicates that it is important to assure that the pitch angle of the blades in the RET is set accurately to zero.

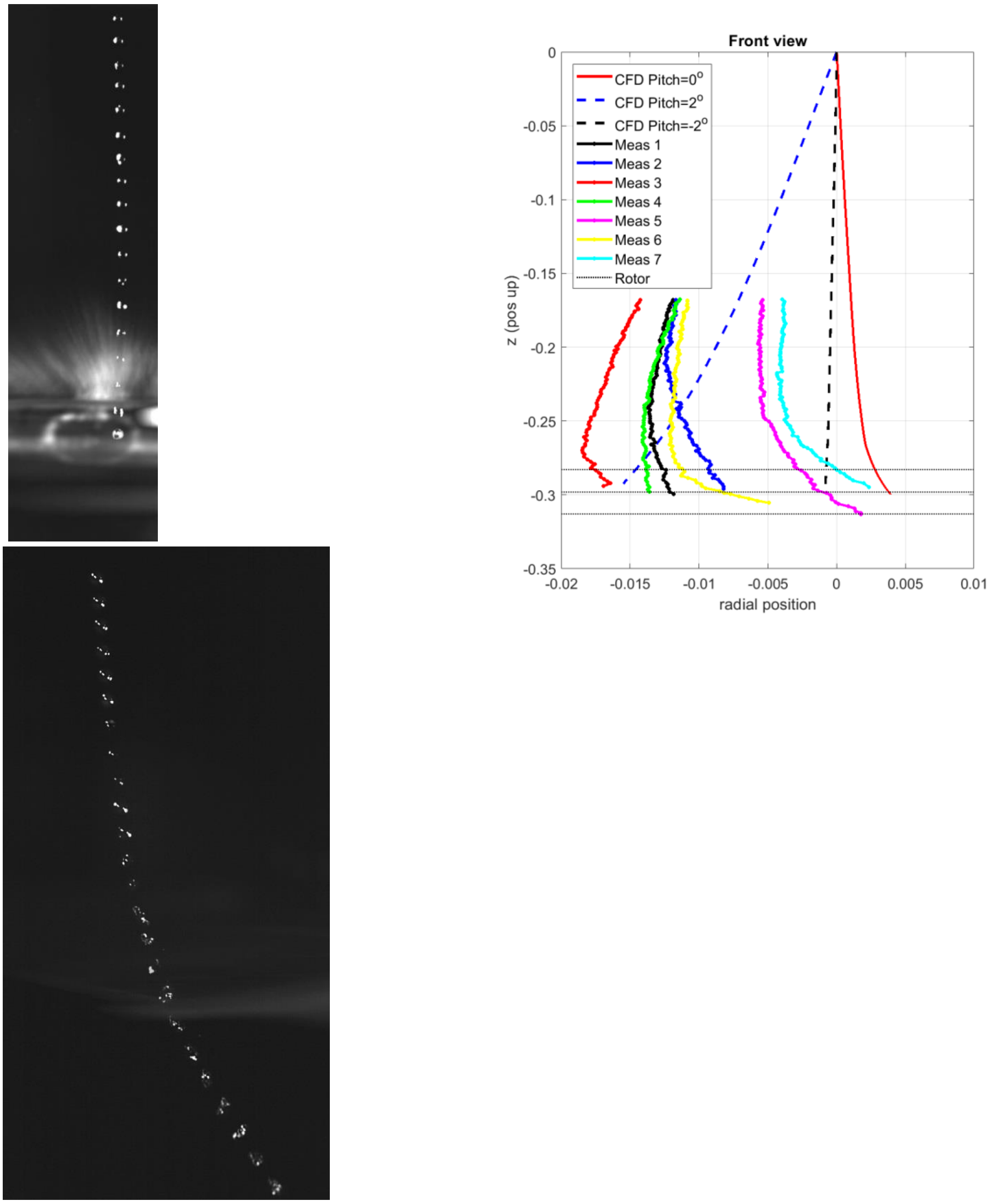


Figure 8: Left and centre pictures; examples of droplet path extracted from high speed videos. Left; seen from the front, 0.0033 seconds between the pictures, centre; seen from the side, 0.002 seconds between the pictures. 1350 RPM, droplet release radius = 1.192m. The right figure shows the comparison of measured and simulated droplet paths in the RET for the front view (vertical and radial positions of the paths). The zero value for the radius is the droplet release radius and positive values are towards the tip.

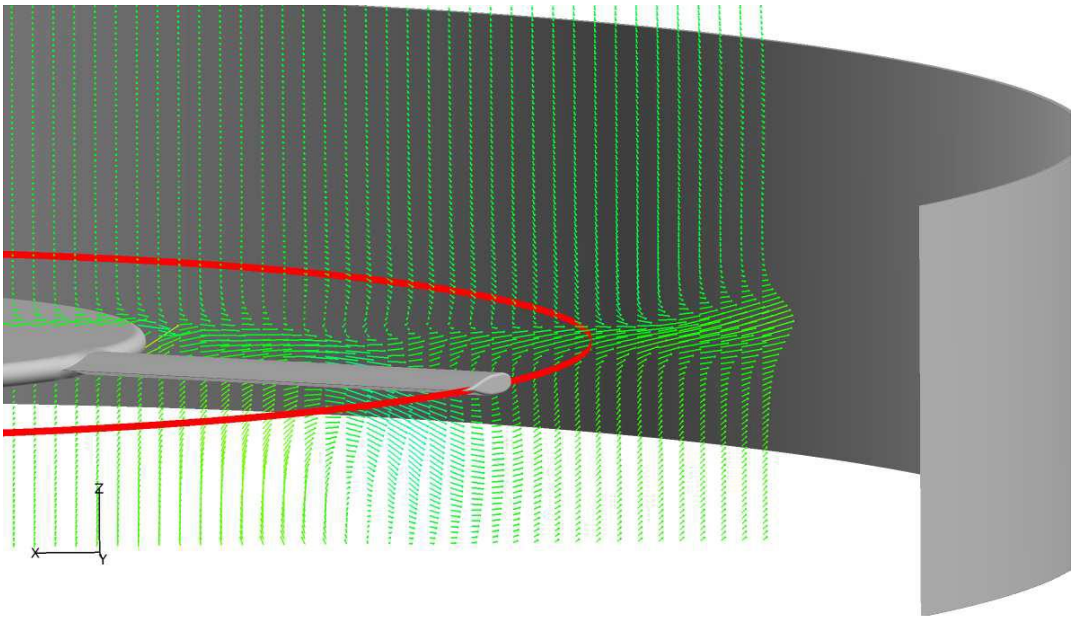
1.5.7 CFD Simulations

A series of high fidelity CFD simulations using the DTU in-house flow solver EllipSys3D have been performed for the Rain Erosion Tester setup, to investigate the effects of different chamber configurations, pitch settings and inflow velocities. The focus was power consumption and flow quality. The general conclusions are that the chamber geometry including the shroud has a very limited effect on the flow around the rotor disk. The effect of the inflow velocity on the power consumption and thrust force is also weak. From a flow quality perspective, the main factor found to influence the flow is the pitch settings of the blades.

Four different configurations were investigated, zero pitch (the present design case), 2 degrees positive pitch (nose up), two degrees negative pitch (nose down) and a special case with two blades at 2 degrees positive and one blade at 2 degrees negative pitch. The zero and 2 degrees positive pitch all showed a very limited effect on the uniformity of the flow above the disk. The minus 2 degrees and the special case both showed quite complex flow above the disk and these configurations should preferably be avoided. The effects on the flow are seen in Figure9 and on the droplets, are seen in Figure.

During the project the EllipSys2D was extended to include compressibility effects. An investigation of the compressible effects on the RET airfoil aerodynamics revealed that the Mach number of 0.3 (which is representative for the Mach numbers seen in the RET) do have some effect on the lift and drag, but compared to the actual forces on the rotor this is of minor importance. The main conclusion with respect to compressibility is that the effect of assuming incompressible flow is valid for investigating the flow patterns in the Rain Erosion Tester.

The 2D simulations concluded that future work on improving airfoil geometry could potentially lower both the power consumption and probably supress vibrations due to flow separation taking place even at very limited angles of attack.



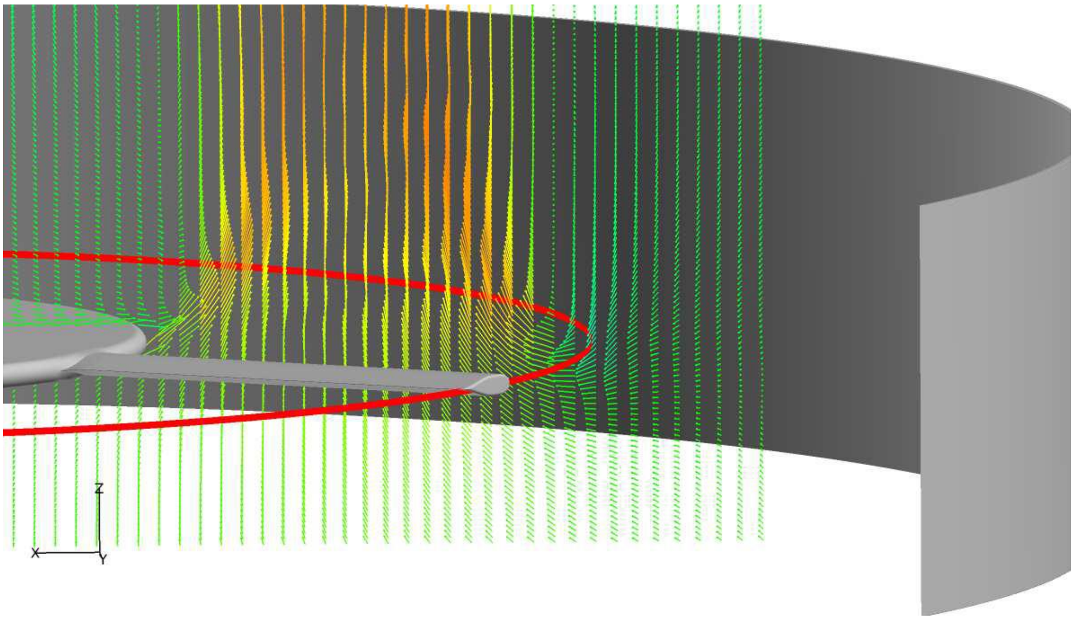


Figure 9: Velocity close to the blade tip. The red line indicates the trace of the tip. Upper figure for 0 degrees. The green colour indicates that the vertical component is downward and very uniform, only close to the rotor plane there is a strong outward component. Lower figure for -2 degrees. The yellow/orange colour in the middle of the blade indicates an upward vertical flow component.

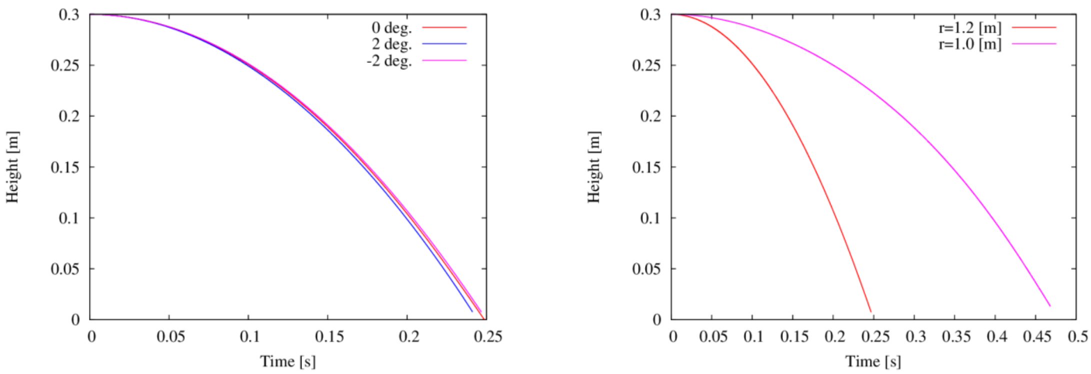


Figure 10: The height of the droplet above the rotor disk as function of time since release. Left figure shows the 0, 2 and minus 2 degrees configurations for a release radius of 1.2 meters (close to the tip) – the falling time is more or less identical. The right figure shows the fall time for a release radius of 1.0 and 1.2 meters for the minus 2 degrees configuration – closer to the centre the effect of the upward vertical flow component is clearly seen.

1.5.8 Leading Edge Roughness (LER) Model

During the project t a modified expression for the turbulent skin friction coefficient used in 2D viscous-inviscid panel methods is developed. The modified expression includes surface roughness effects and is therefore believed to be an improvement to the modelling of LE roughness (LER) effects on air foils.

It is still relevant to use panel methods as they are faster and simpler to use than CFD methods. Panel methods are also relatively accurate for thinner air foils (up to a relatively thickness of approximately 30%). Hence, they are very usable to get a first indication of the air foil performance for a large range of angle of attacks and Reynolds numbers.

1.5.9 List of publications derived from this project

- Anthony Fraisse, Jakob Ilsted Bech, Kaj Kvisgaard Borum, Vladimir Fedorov, Nicolai Frost-Jensen Johansen, Malcolm McGugan, Leon Mishnaevsky, Yukihiro Kusano; "Impact fatigue damage of coated glass fibre reinforced polymer laminate", submitted to "Renewable Energy"

- Yukihiro Kusano, Nicolai Frost-Jensen Johansen, Jakob Ilsted Bech; "Comparison of surface treatment methods for durability against high speed impacts". In preparation, and will most likely be submitted to Surface Engineering.

- M Gaunaa, N N Sørensen, N Frost-Jensen Johansen, A S Olsen, C Bak and R B Andersen; "Investigation of droplet path in a rain erosion tester", poster for the TORQUE 2018 conference.

- A S Olsen, N Ramos-García and C Bak; "Improved Roughness Model for 2D Viscous-Inviscid Panel Methods", in preparation. Planned to be submitted to Wind Energy Science.

- Mads Erik Mathiesen, Gitte Lund; Case story "R&D A/S' Rain Erosion Tester for LM Wind Power" published at http://www.rdas.dk/en/cases/energy/ret-for-lm/)

- Martin Bonde Madsen, Rasmus Bush Andersen; "*Rain Erosion: Correlation Between Laboratory Testing and Real Life Exposure*", in preparation. Planned to be submitted to AMI Wind Turbine Blade Manufacture Conference.

Conferences:
- Wind Energy Science Conference (WESC) 2017, June 2017, Lyngby, Denmark
- TORQUE 2018, June 2018, Milano, Italy
- AMI Wind Turbine Blade Manufacture Conference, December 2018, Dusseldorf, Germany

1.6 Utilization of project results

A recommend practice for rain erosion test of wind turbine blades is being developed by DNV-GL based on the R&D RET unit and the basic knowledge on rain erosion testing developed in this EUDP project.

Market situation for the developed R&D RET unit is as follow by March 2018:

- **1 RET unit at R&D (EUDP funded)**
- **5 RET units sold to customers in wind energy sector**
- **8 RET unit Quotations being evaluated by 8 new customers active in wind energy sector**

R&D expect the unit also to be useful in Aerospace and other transport industries with a rain erosion challenge (units with high speed and exposed to rain)

Competitor RET units are only found to be local units developed by players in wind energy sector like Poly-Tech, Mankiewicz, Fraunhofer IWES, University of Dayton Research Institute, Universitat de Barcelona. None of these players market their own developed units, they have only designed and manufactured them for own needs. This lead to the conclusion that there are no other commercial available RET units at the market today.

1.7 Project conclusion and perspective

The objective of this project was to develop state-of-the-art technology within rain erosion testing. The aim is that R&D wants to market a rain erosion tester, RET, which enables an accurate and repeatable simulation of erosion combined with valid data collection.

A RET provides an opportunity for the coating / blade / wind turbine manufacturers to test what surface that will provide the best endurance under rain exposure. This is very hard to perform theoretically and thereby the RET offers manufacturers a mean to identity and understand the risk of unexpected damages caused by erosion and thereby lower the cost of energy.

The R&D RET test unit developed in this project has proven to have a high repeatability in the tests performed by demonstrating a Coefficient of Variance (COV) below 10%.

Valid data collection has been developed in this project as an in-line Vision system documenting erosion test results during test to follow the erosion development over time.

The overall goal is to enable a reduction in the operational expenditure for the wind energy sector and thereby lower the cost of energy. By using the R&D RET to test what surface can provide the best endurance under rain exposure the surface manufactures can easy and fast test their developments to get to successful surface solution for wind turbine blades. Wind turbine manufacturers can also use the RET unit to test which surface suppliers are the best to use when designing new turbine blades. All of them can document their test results and compared with others test results when using the R&D RET unit for their rain erosion test.

All in all, R&D A/S and DTU have made a successful rain erosion test unit proof of concept. This is demonstrated by accomplished sales of 5 R&D RET units to 5 different customers within the wind energy sector. The unit is market today by online marketing, conference attendance and by contacting relevant customers directly. Already 8 other customers in the wind energy sector are considering a purchase of a R&D RET unit of today. This correspond to yearly expected sales of 8-16 mio.DKK.

The distribution of the R&D RET unit demonstrates increased development activities in the wind energy sector to reduce the rain erosion issue on wind turbine blades leading to lower cost of energy.

R&D has also experienced an interest from other industries like aerospace, train transport - industries with a rain erosion challenge having units with high speed and exposure to rain. This could lead to that the R&D RET unit could be market in other areas than wind energy sector.