



Experimental and numerical study on the impact force of water droplets in the medium speed regime

Aya Aihara¹ and Motofumi Tanaka^{1,2}

¹National Institute of Advanced Industrial Science and Technology, 2-2-9, Machiikedai, Koriyama, Fukushima 963-0298, Japan

²Kyushu University, Open Innovation Build., 6-1, Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan

Correspondence: Aya Aihara (aya.aihara@aist.go.jp)

Abstract. This study investigated the impact force exerted by a water droplet colliding with a solid surface at medium velocities. Raindrop impacts on wind turbine blades can cause erosion damage, reducing the power efficiency. Addressing this issue is of practical importance for wind energy. Previous studies have revealed that the droplet impacts can be scaled with inertial force, expressed as $\rho D^2 V^2$, where ρ , D , and V are water density, droplet diameter, and impact velocity, respectively.

- 5 This study examined whether this scaling can be applied under conditions representative of raindrop impacts on wind turbine blades, where the impact velocity is relatively high, ranging from 35 to 126 m/s. To this end, the impact force of millimeter-sized droplets was measured using a whirling arm rain erosion tester and a pressure sensor. Computational fluid dynamics simulations were conducted to model the experimental conditions. The simulation results, assuming an ideal spherical droplet, showed the scaling of $\rho D^2 V^2$ for the impact force. The experimental data generally followed the scaling law; however, the
- 10 peak impact forces tended to be slightly higher. Images of the droplets before impact indicate that the droplets were significantly deformed by the high-speed airflow in the vicinity of the rapidly rotating blade. To accurately evaluate impact forces at moderate-to-high velocities, it is necessary to account for aerodynamic effects on the droplets rather than assuming a spherical shape.

1 Introduction

- 15 With the currently increasing rotor size of turbines, leading-edge erosion of wind turbine blades has become a critical issue. Erosion is caused by several factors, such as raindrops, sand grains, and ice particles, and blade materials are often damaged by being subjected to repeated loads from these particles. A combination of these external loads and other chemical factors, such as UV radiation from the sun or salty seawater, can accelerate the progress of fatigue damage. Consequently, the surface roughness of eroded wind turbine blades may increase, degrading blade performance. Therefore, blade coatings should be
- 20 applied to the leading-edge erosion in both onshore and offshore wind turbines. However, the maintenance of repairing or reattaching coatings is required in many cases because the development of highly robust coating materials is still underway.

Efforts to understand the mechanisms of erosion damage from meteorological, material, and aerodynamic perspectives have intensified in recent years. Since precipitation is a key factor, understanding the relationship between environmental conditions at wind farms and the progression of leading edge erosion is essential. Hasager et al. (2020) evaluated leading edge erosion



25 rates and expected lifetimes under different precipitation conditions. Slot et al. (2015) stated that the coating lifetime can be predicted based on the Palmgren and Miner rule (Miner, 1945) by considering parameters such as rain intensity and droplet diameter as variables. Eisenberg et al. (2018) predicted erosion on operating wind turbine blades based on the Springer equation (Springer, 1976), rain conditions, and the erosion resistance of coating materials, and compared the predictions with images of actual blade damage. The study by Amirzadeh et al. (2017a) and Amirzadeh et al. (2017b) used CFD simulations to calculate the impact pressure of droplets of various diameters and finite element analysis to evaluate fatigue damage resulting from repeated raindrop impacts for the prediction of erosion lifetime of wind turbine blades. Barfknecht and von Terzi (2025) predicted erosion damage to leading-edge coatings on wind turbine blades using their proposed model and concluded that droplet diameter has a significant influence on erosion. Erosion damage further reduces wind turbine performance. Sareen et al. (2014) observed increased drag and decreased lift in wind tunnel tests, and Panthi and Iungo (2023) estimated AEP loss based on observed transition locations on the turbine blade and the BEM analysis. Bech et al. (2018) showed that appropriate turbine control can mitigate erosion damage without significant AEP loss.

The erosion tests are widely conducted to evaluate the durability of coating materials, and many studies have investigated the relationships between material durability and various factors, including droplet impact conditions and material properties. Bech et al. (2022) conducted rain erosion tests with different droplet diameters, proposed a method for characterizing material durability as a function of droplet diameter, and emphasized the importance of considering droplet diameter for accurate lifetime prediction. When a raindrop impacts a material surface, a compressive wave is generated and propagates within the material, depending on its stiffness and hardness (Herring et al., 2019). Katsivalis et al. (2022) reported correlations between material properties and erosion resistance. Factors such as coating thickness, interfacial adhesion, and surface roughness have also been shown to affect coating performance (Hoksbergen et al., 2023; Cortés et al., 2017; Tempelis et al., 2024). Jones et al. (2023) proposed a method for evaluating material durability by combining erosion testing with dynamic mechanical analysis (DMA), thereby accounting for the thermomechanical properties of the material. While material durability has been evaluated through laboratory-scale experiments, understanding the relationship between erosion damage and test conditions is essential for accurately assessing erosion under actual wind turbine operating conditions.

Understanding the dynamics of droplet impact at moderate-to-high velocities is necessary to obtain optimal solutions for the leading-edge erosion problem of wind turbines. The tip speed of the blades can be close to 100 m/s for 10-MW turbines, at which speed rain droplets collide with the blade surfaces. Knowledge regarding raindrop impact in this velocity regime is limited; however, directly observing the droplet impact on wind turbine blades is challenging. Elucidating the relationship between various conditions, such as droplet size distribution, impact velocity, droplet shape, and the resulting impact force, can enable the estimation of the forces exerted by raindrops on turbine blades, causing rain erosion, under different weather conditions. As a result, appropriate countermeasures, such as the use of suitable coating materials and optimized wind turbine control strategies, can be implemented.

The droplet impact has been extensively investigated. Cook (1928) first proposed a water hammer equation representing the high pressure generated by a compression wave in a liquid impacting a solid. The pressure is expressed as ρcV , where ρ is the density of the liquid, c is the speed of sound in the liquid, and V is the impact velocity. One-dimensional stress



60 wave propagation was assumed in the derivation of the water hammer pressure. It was pointed out by De Haller (1933) that the pressure expressed above is only valid for the liquid impact on a rigid surface. Engel (1955) derived the modified water hammer equation, expressed as $0.5\alpha\rho cV$, where a factor of 0.5α was obtained because of the spherical shape of the droplet. Heymann (1969) proposed a two-dimensional approximation of the impact pressure, showing that the pressure at the contact edge could increase by up to three times the water hammer pressure for water droplet collision. This increase in impact pressure, which is
65 larger than the water hammer pressure, has also been reported in other studies (Li et al., 2011; Zhou et al., 2009). Field et al. (1985, 1989) investigated the effect of liquid-drop impact on the damage and erosion of materials. Their findings primarily addressed droplet impacts in the high-speed regime.

Several studies have investigated the relationship between the impact force and parameters such as droplet diameter D and impact velocity V , demonstrating that the impact force F is described with a scaling of $\rho D^2 V^2$ at high Reynolds number,
70 $Re = DV/\nu$, where ν is the kinematic viscosity of the liquid. From a fundamental standpoint, the force can be expressed as $F = mV/\Delta t$, based on the impulse–momentum, where m is the droplet mass. Considering that m and Δt are proportional to D^3 and D/V , respectively, the force can be scaled with D^2 and V^2 . Gordillo et al. (2018) and Cheng et al. (2022) stated that the peak force should be scaled with the inertial force $\rho D^2 V^2$, instead of the water-hammer force, $\rho D^2 cV$, where c is the speed of sound in the liquid, for an impact velocity less than c . Soto et al. (2014) expressed the impact force is proportional to V^2 ,
75 representing the inertial nature of the collision. They showed that the measured forces of a millimeter droplet can be expressed as $F = \pi\rho D^2 V^2/4$, representing a dynamic pressure ρV^2 applied over a surface area $\pi D^2/4$. Zhang et al. (2017) showed that the peak force is proportional to $\rho D^2 V^2$ for the high Reynolds number, $Re > 230$, where the inertia is dominated. Li et al. (2014) reported that the peak force is a power function of D and V based on their experiments on free-fall water droplets. Mitchell et al. (2016) showed that the impact force for a water droplet impacting at low velocities of up to 3.3 m/s can be
80 expressed as a function of V^2 . Most studies have considered free-fall droplets with the low impact velocities; however, free-fall experiments can produce impact velocities of only approximately 6 m/s for millimeter-sized droplet because of their terminal velocity. As demonstrated by Zhou et al. (2024), who calculated droplet impact forces at 110 m/s using a fluid-solid coupled model, numerical analysis can reproduce high-speed impacts, but numerical studies on impact force scaling remain limited.

This study investigated the impact force of a water droplet impacting a rigid wall at a high Reynolds number under medium-
85 speed impact conditions. We examined whether the impact force under conditions typical of raindrop collisions on wind turbine blades follows the scaling of $\rho D^2 V^2$. Specifically, these conditions involved droplet diameters of several millimeters and impact velocities ranging from 35 to 126 m/s, corresponding to Reynolds numbers ranging from 2×10^4 to 5×10^5 . Previous studies have shown that the normalized force $F_{peak}/\rho D^2 V^2$ remains constant in a high Reynolds number regime. Although these studies experimented on liquids with different viscosities at various Reynolds numbers, few measurements were performed
90 with varying impact velocities because of limitations in the experimental setup. In this study, we used a Rain Erosion Tester (RET), which is a whirling arm test facility that can spin blade specimens at a high velocity to reproduce the droplet impact exerted on wind turbine blades. The impact force was measured using a pressure sensor flush-mounted on the rotating blade specimen. The moment of droplets colliding with the surface was captured using a high-speed camera. Five needle sizes were used to produce droplets with different diameters. Additionally, three-dimensional CFD simulations for incompressible flows

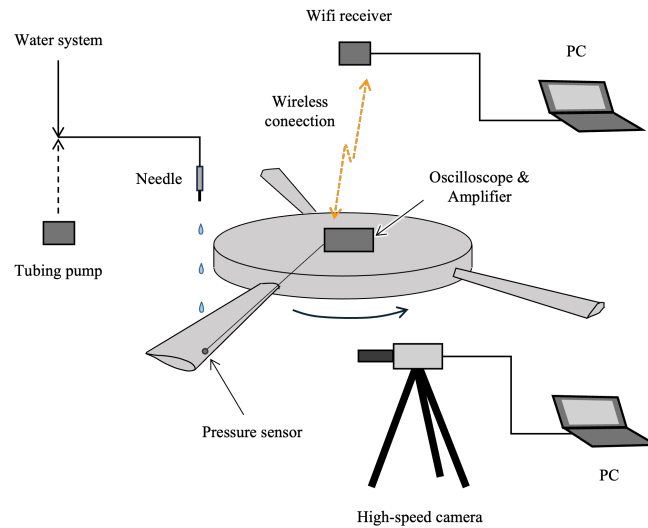
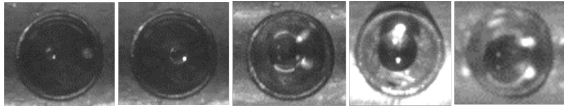


Figure 1. Schematic of the experimental setup.

Table 1. Sizes and inner diameters of the five types of needles used in the experiments. Photographs showing examples of a droplet before impacting with the pressure sensor for each four cases.

					
Water supply	Tubing pump		RET water system		
Needle size	G28	G24	G32	G27	G20
Inner diameter of the needle [mm]	0.17	0.30	0.10	0.20	0.58

were conducted to reproduce the experimental conditions. We verified whether both the measured and simulated impact forces can be represented by scaling based on the inertial force at a high Re regime.

2 Study method

2.1 Experimental approach

The impact force of a water droplet was measured using a whirling arm rain erosion tester with a pressure sensor flush-mounted on a blade specimen. Part of the experimental procedure has been described in a previous study (Fujisawa et al., 2024). Figure 1 shows a schematic of the experimental setup. A pressure sensor (PCB Piezotronics, 113B24) was used, which has the measurement range of up to 6895 kPa, sensitivity of 0.743 mV/kPa, and the nonlinearity within 1.0% of full scale. The limit of rise time is 1.0 μ s or less. The sensor manufacturer provided the sensitivity obtained using two methods: the

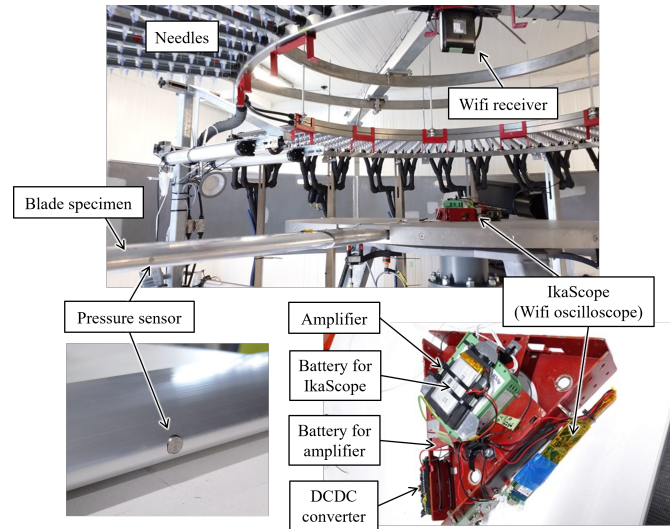


Figure 2. Experimental setup in the test facility.

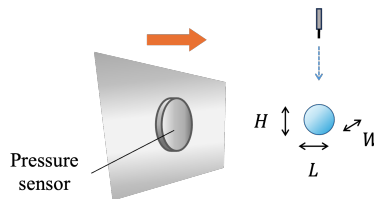


Figure 3. Definition of the directions of droplet dimensions for height H , width W , and depth L , relative to the impacting surface of the pressure sensor.

Aronson Calibrator and the Pulse Calibrator, both of which evaluate the sensor characteristics by applying a pressure pulse.

105 The pressure sensor has a resonant frequency of at least 500 kHz and the low frequency response of 0.005 Hz. Based on the sensor frequency response, the upper limit of the ± 3 dB response range is half of the resonant frequency (≥ 250 kHz). The pressure sensor was embedded in one of the three blade specimens at the leading edge, as shown in the bottom-left picture in Fig. 2. Its sensing area has a diameter of 5.54 mm. The output of the pressure sensor was signal-processed using an amplifier (PCB piezotronics, 682A02) powered by a 24V DC/DC converter. The output signal was transmitted to a wireless oscilloscope (IKALOGIC, IkaScope WS200) with a 200-MHz sampling rate installed with batteries at the center of the rotor to collect the sensor output, as shown in the bottom-right picture in Fig. 2. The signal stored in the oscilloscope was transmitted wirelessly to the receiver attached to the support columns above the rotor. The data were monitored using commercial software designed for the IkaScope and saved on a PC connected to the receiver. The impact force was obtained by multiplying the low-pass filtered pressure by the sensing area. In this measurement, the droplet impact produced a concentrated point load rather than

115 a uniformly distributed surface load on the pressure sensor as in the manufacturer's calibration. Therefore, the sensor voltage



Table 2. List of the numbers of measurements conducted using five different needles at different impact velocities presented with the rotational speed of the rotor.

	G28 (p)	G24 (p)	G32	G27	G20
35 m/s (300 rpm)	5	12	7	4	8
70 m/s (600 rpm)	5	13	0	7	5
94 m/s (800 rpm)	0	0	0	6	3
100 m/s (854 rpm)	5	11	4	6	5
105 m/s (900 rpm)	0	0	3	0	0
111 m/s (950 rpm)	0	0	0	4	0
126 m/s (1080 rpm)	5	12	2	9	5

output was recalibrated using known droplet momentum value. The detailed procedure for the correction will be described later.

The RET was equipped with 600 needles, but only one needle was used, and the rest were covered with plastic plates to prevent droplets from falling. The selected needle was placed at a radius of 1.118 m. Three needles of G32, G27, and G20 sizes were used to generate droplets with diameters greater than 2 mm (Table 1). The flow rate, controlled by the water system of the RET, was adjusted to produce the desired droplet size. For measurements using the G27 needle, the flow rate applied to all 600 needles was 60 L/hour, which corresponds to a flow rate for a single needle of 1.67 mL/min. For the measurements using the G32 and G20 needles, the flow rates for all needles were 120 and 20 L/hour, respectively. The RET consists of 60 manifolds, each equipped with 10 needles. For the manifold used in the measurements, all 10 needles were G32 needles when using the G32 configuration. In contrast, when using the G20 configuration, no needle was installed at the innermost position, and G20 needles were attached to the remaining nine positions. In both cases, G27 needles were installed on the other 59 manifolds. A tubing pump (AS ONE, DSP-100SA) was used to generate droplets with diameters less than 2 mm without using the RET water system. A tubing pump was introduced because small droplets could not be produced by fine-tuning the flow rate using the RET. A single G28 or G24 needle, connected to the tubing pump, was placed at the same radius as the other three needles. The flow rate was set at 4 mL/min. Because a thinner needle produces mist rather than droplets, droplets with diameters smaller than 0.5 mm could not be generated.

Images of droplet impacts were captured by a high-speed camera (Photron, FASTCAM Nova S12) to evaluate the position of the droplet at the impact on the sensor and the shape of the droplet (height H and width W as illustrated in Fig. 3). They were recorded at 50,000 frames per second with a shutter speed of 20 μ s. For measurements using a G27 needle, images of droplets were captured simultaneously from the side (radial) direction with another high-speed camera (Phantom, VEO 440 L) at 12,000 to 30,000 frames per second with a shutter speed from 1 to 6 μ s. In this study, the aspect ratio is defined as the ratio of H to W . The droplet diameters were measured using the disdrometer (OTT HydroMet, OTT Parsivel²). In the following discussions of the experimental data, D denotes the droplet diameters measured by the disdrometer.



The numbers of measurements for the five needle cases and the impact velocities are presented in Table 2. Only data were
 140 used for calculations when the droplet hit around the center of the sensing surface of the sensor; thus, the peak impact force
 was accurately measured even the droplet spread out on the sensing surface after impact. In total, 68 and 78 measurement data
 points were obtained for the cases using the tubing pump and the RET water system, respectively.

2.2 Numerical model

2.2.1 Governing equations

145 In this study, computations were performed for two immiscible flows to model a phenomenon that a spherical droplet impacting
 orthogonally on a rigid plane surface. The governing equations for incompressible flows are presented below.

The interface between liquid and gas was tracked using the volume of fluid (VOF) method developed by Hirt and Nichols
 (1981). The phase fraction α is introduced to determine the region of each phase, i.e., $\alpha = 1$ for the liquid and $\alpha = 0$ for the
 gas phase. The MULES algorithms (Rusche, 2003) was applied to maintain the boundedness of α , i.e., $0 \leq \alpha \leq 1$. The solver
 150 considers a mixture of two phases as a single fluid; therefore, the density ρ and dynamic viscosity μ are calculated as the
 weighted average of two phases, expressed as

$$\rho = \alpha \rho_l + (1 - \alpha) \rho_g \quad (1)$$

and

$$\mu = \alpha \mu_l + (1 - \alpha) \mu_g. \quad (2)$$

155 Phase transitions were not considered in this study.

The governing equations of continuity, momentum, and phase fraction are

$$\nabla \cdot \mathbf{u} = 0 \quad (3)$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p_{rgh} + \nabla \left(\mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right) + \rho \mathbf{g} + \mathbf{f}_s \quad (4)$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) + \nabla \cdot (\alpha (1 - \alpha) \mathbf{u}_r) = 0 \quad (5)$$

160 where μ is the dynamic viscosity, $\mathbf{I}$ is the identity tensor, $\mathbf{g}$ is the gravitational acceleration, $\mathbf{f}_s = \sigma \kappa \nabla \alpha$ is the surface tension
 force, σ is the surface tension, and κ is the curvature of the free surface. The velocity is assumed to be proportional to the

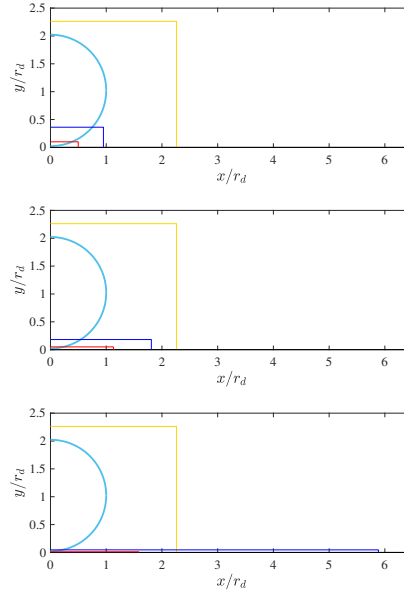


Figure 4. Schematics of the droplet CFD model illustrated with the regions representing the mesh resolution level. The light-blue circle at the center indicates the initial position of the droplet. The resolution in the regions enclosed by the red, blue, and yellow boxes correspond to the refinement levels that resolve the droplet diameter with 1131, 566, and 35 cells, respectively. The top, middle, and bottom plots represent the meshes used during the initial, intermediate, and final stages of droplet spreading, respectively. The meshes are symmetric with respect to the y-axis.

contributions from each phase, i.e., $\mathbf{u} = \alpha \mathbf{u}_l + (1 - \alpha) \mathbf{u}_g$. The subscripts l and g indicate the liquid and gas phases, respectively. $\mathbf{u}_r$ is the relative velocity between the two phases and is modeled as $\mathbf{u}_r = C_\alpha (|\phi|/S_f) \mathbf{n}_f$ where C_α is a user-specified value, ϕ is the face volume flux, $\mathbf{n}_f$ is the face unit normal vector, and S_f is the face area. The dynamic pressure p_{rgh} is the total pressure minus the hydrostatic pressure defined as

$$p_{rgh} = p - \rho \mathbf{g} \cdot \mathbf{x} \quad (6)$$

where $\mathbf{x}$ is the position vector.

2.2.2 Numerical setup

Three-dimensional two-phase flow simulations were performed using the interFoam solver in OpenFOAM v2106, which employs the VOF method to capture the interface between the liquid and gas phases. Pressure-velocity coupling was handled using the splitting of operators (PISO) algorithm with three corrector steps per time step. The pressure equation was solved



using a GAMG solver with a tolerance of 10^{-7} , whereas the velocity and phase-fraction equations were solved using a smooth solver with tolerances of 10^{-6} and 10^{-8} , respectively. Each time step was adjusted such that the maximum Courant number was limited to 0.1. The gravity effect $|g| = 9.81 \text{ m/s}^2$ in the momentum equation was considered. The flow was assumed to be laminar, and no turbulence model was employed.

Temporal discretization was performed using the Crank-Nicolson scheme with a blending coefficient of 0.5. The convective term in the momentum equation was discretized using the first-order upwind scheme, whereas the van Leer scheme was employed for the advection of the phase fraction. The gradient terms were evaluated using the Gauss linear scheme, and the Laplacian terms were discretized using the Gauss linear corrected scheme.

Both water and air were treated as incompressible Newtonian fluids. The density and kinematic viscosity were 996.6 kg/m^3 and $1.049 \times 10^{-6} \text{ m}^2/\text{s}$ for water, and 1.225 kg/m^3 and $1.461 \times 10^{-5} \text{ m}^2/\text{s}$ for air, respectively. The surface tension coefficient between water and air was $\sigma = 0.073 \text{ N/m}$. The surface tension σ was set to 1, with two phase-fraction correctors and one subcycle.

A no-slip boundary condition was imposed on the impact surface boundary. No explicit contact-angle boundary condition was imposed on the solid surface.

The same three-dimensional structured meshes were used as those applied in our previous study (Aihara et al., 2024), validated using low-speed droplet impact measurements. At $t = 0$, the initial droplet position was set with a gap of $0.011D$ between the bottom of the droplet and the wall surface. The computational domain was $90.5D$ in both width and depth and $22.6D$ in height from the wall surface to the top boundary. Three different meshes with different refined mesh areas were used at each droplet spreading stage in one simulation case, as shown in Fig. 4. After computing the time required for the spreading droplet to reach the boundary of the blue-box region, the flow fields at the last time step were mapped onto the next mesh, and the simulations were continued. Outside the high-resolution regions, indicated by the yellow-box region, the droplet was discretized with 35 cells per diameter. The numbers of cells for those three different meshes were 67, 116, and 185 millions, respectively.

The instantaneous impact force was calculated by integrating both the pressure and viscous forces over the impact surface. The static pressure p , reconstructed from p_{rgh} , was used for the evaluation of the pressure contribution. The impact force presented in this study was defined as the component of the integrated force normal to the impact surface.

Table 3 presents the six simulation cases, including three different droplet diameters and two different impact velocities, tested in this study.

All computations were performed using a Wisteria supercomputer operated by the Information Technology Center at the University of Tokyo. The simulation node group is equipped with a FUJITSU Processor A64FX 2.2 GHz frequency. Parallel computations were conducted using a maximum of 1152 processors with 24 nodes. The maximum CPU time for the six simulation cases was 187 h.



Table 3. List of six simulation cases using the CFD model. Three different droplet diameters D and two different impact velocity V were considered.

CASE	D [mm]	V [m/s]
1	1.0	35
2		126
3	2.0	35
4		126
5	3.0	35
6		126

Table 4. Mean values, standard deviations, and the coefficients of variation for the droplet diameter for different five needles that were measured using the disdrometer.

Water supply		Tubing pump		RET water system		
Needle		G28	G24	G32	G27	G20
Diameter	Mean [mm]	0.70	1.01	2.16	2.52	3.17
	Standard deviation [mm]	0.867	0.205	0.124	0.089	0.236
	Coefficient of variation	1.245	0.204	0.058	0.035	0.074

3 Results and discussion

205 3.1 Experimental Results

The mean values and standard deviations of the droplet diameters are presented in Table 4. In this experimental setup, mean droplet diameters in the range of 1 to 3 mm can be generated. Although the coefficient of deviation for the G20 needle exhibits a relatively larger value, those for the other needle cases increases as the droplet diameter decreases. With the RET water system, droplets were generated by static dripping at the needle tip under low flow rate conditions. In contrast, the use of the tubing pump resulted in a higher flow rate, where a continuous liquid column broke up dynamically into droplets during the fall. This difference in droplet formation mechanisms likely caused the differences in the coefficients of variation.

To examine three-dimensional droplet shapes, imaging was conducted from the radial direction of the rotor on the outer side of the blade for measurements using a G27 needle. Figure 5 shows images of the droplet impact viewed from two directions. Because the blades rotated at a high speed, the falling droplet could be considered almost stationary with respect to the blade. The images show that the droplets splashed out on the sensor surface. The time interval between successive falling droplets generated using a G27 needle was measured, and the mean value of the period was approximately 0.3 s. This interval was sufficiently long for a droplet to spread out. Even if the probability of collision is assumed to be 100%, which practically is substantially less, the water film on the pressure sensor was considered to become sufficiently thin before a subsequent collision.

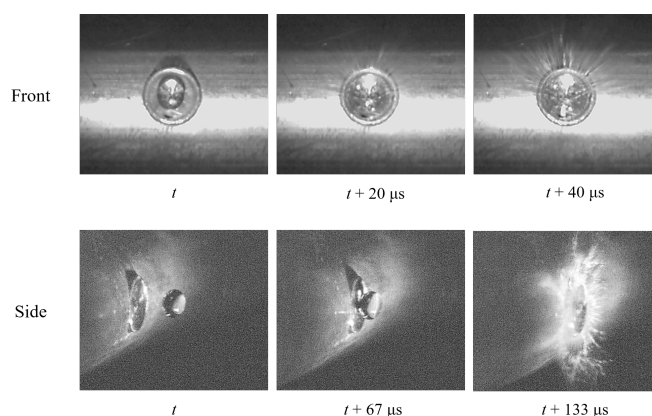


Figure 5. Images of droplets before and after impact captured simultaneously using two high-speed cameras placed in the front and side directions. The impact velocity is 35 m/s, and the droplet diameter is 2.7 mm. Images captured in the front and side directions were not synchronized; therefore, each time t did not necessarily represent the same moment.

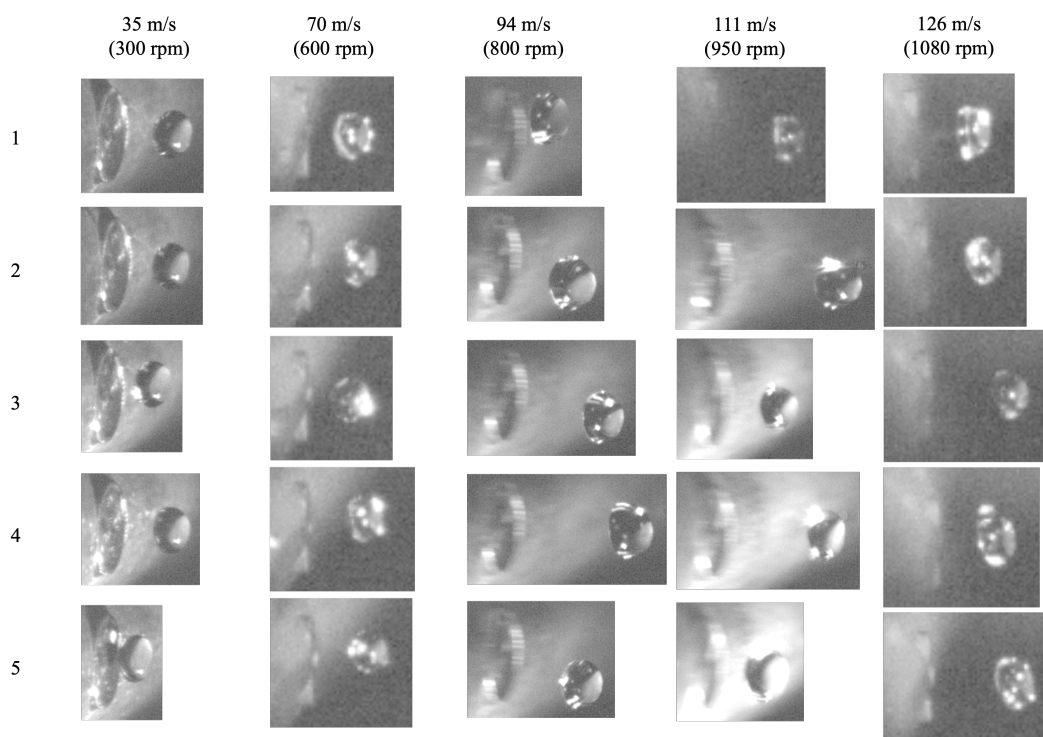


Figure 6. Examples of droplet profiles captured one or two frames before the onset of impact at different impact velocities viewed from the side. All images are of droplets generated using the G27 needle. Each image represents data from a single measurement, and they do not indicate a time sequence.



220 Since the droplet shape has a significant influence on the impact force, it is important to examine the droplet shape. Figure 6 shows some images of impacting droplets at selected impact velocities. The droplets exhibited elongated elliptical shapes at 35 m/s but became more bowl-shaped with the bottoms facing the sensor at a velocity of 94 m/s. The droplets were no longer symmetrical but rather irregular and distorted at an even higher velocity of 126 m/s. Although only a few images are presented here, the dependency of the droplet profile on the impact velocity exhibits an overall trend. These images indicate that
 225 the droplets were subjected to aerodynamic forces when approaching the high-speed airflow around the blade before impact, affecting the droplet shape. Therefore, perfectly spherical droplets were rarely observed in measurements. Barfknecht and von Terzi (2024) considered raindrop impacts on wind turbine blades and indicated that the aerodynamic interactions between the flow around the blade and droplets affect the droplet shape.

It is worth noting that the droplet undergoes deformation in two stages during its fall. We experimentally observed that, when
 230 a droplet released from a needle reached the region swept by the rotating blades, that is, when the approaching blade was still at a certain distance from the droplet, the shape of the droplet suddenly changed from spherical to ellipsoid or irregular. This was caused by the swirling flow generated by the rotating blades. Then, just before impact, the droplet is further deformed as it is compressed by the high-speed airflow in the immediate vicinity of the blade's leading edge.

While the droplet shape was qualitatively examined from images in Fig. 6, Fig. 7 provides a quantitative evaluation of the
 235 droplet dimensions in three direction, showing the three-dimensional shape trends for each needle case. For the G32 needle, both H' and W' are greater than 1, indicating that the dimensions in these two directions exceed those measured by the disdrometer, i.e., those in the absence of aerodynamic deformation. In contrast, for the G20 needle, both H' and W' are close to 1, indicating no significant deviation from the original droplet shape. Regarding L' , the values for the G32 case decreases from 1 as the impact velocity increases, suggesting that the droplet tended to flatten in the direction normal to the pressure sensor
 240 surface. For the G20 case, L' values are scattered around 1, indicating little anisotropy among the three dimensions. The G27 needle case exhibits trends similar to those of the G32 case in terms of the droplet dimensions in the three directions.

Regardless of the needle type, the droplets tended to be vertically elongated. The aspect ratio is greater than 1 below the line $H' = W'$ in the left plots of Fig. 7, whereas it is less than 1 above the line. Most data points lie below this line, indicating the aspect ratios higher than 1. The droplet underwent free fall while periodically alternating between an elongated vertical
 245 shape and an elongated horizontal shape. Probably, the distance between the needle tip and blade height, that is 400 mm, corresponded to the height at which the droplet became vertically elongated.

The calibration procedure for the pressure sensor in the present study is described below. The calibration value of the pressure sensor published by the manufacturer is 0.743 mV/kPa. The calibration is conducted under uniformly distributed loading conditions. However, our experiments were conducted under conditions where the sensing surface was subjected to a
 250 point load by a droplet rather than a uniformly distributed load. The point load on the sensing surface could yield an inaccurate output of the signal because the sensor diaphragm was unevenly deformed. Therefore, to address this effect, the sensor was recalibrated as the published calibration value was not applied to the present case. This experiment considered the force acting in the direction normal to the impacting surface. Because the surface was flat, the normal component of the momentum

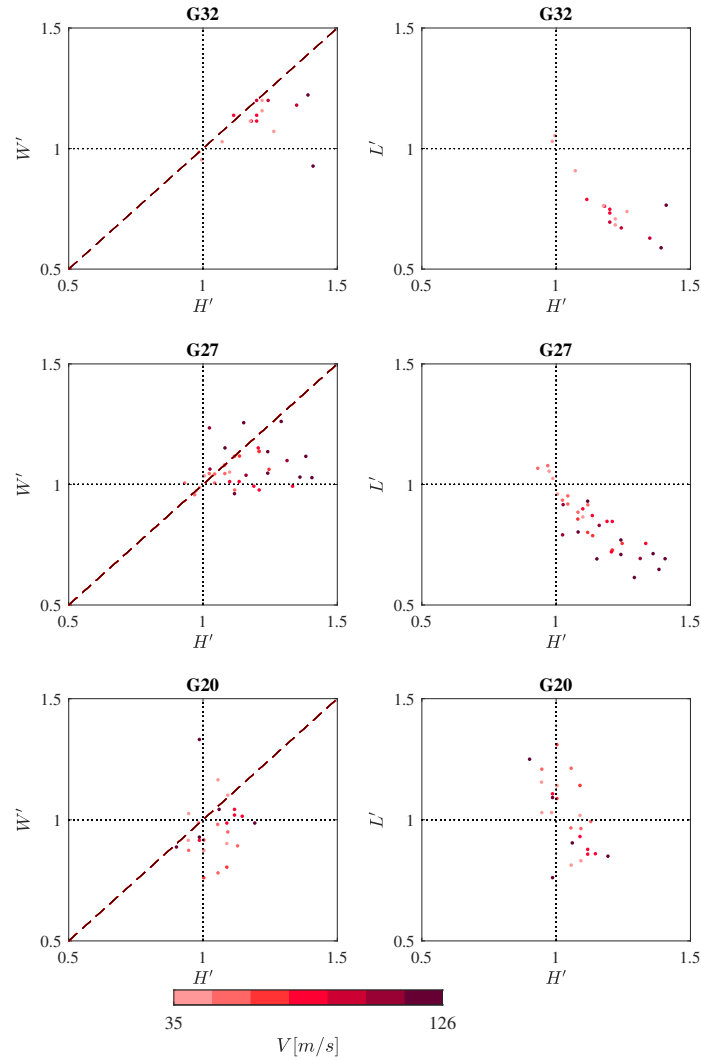


Figure 7. Relationship between the normalized droplet height $H' = H/D$ and width $W' = W/D$, determined from high-speed camera images (left plots) and the relationship between H' and the dept $L' = L/D$, estimated under the assumption of constant droplet volume for each needle as $L = D^3/(HW)$ (right plots). The variables H , W , and L are normalized by the mean droplet diameter D measured using the disdrometer. The top, middle, and bottom rows correspond to the cases using the G32, G27, and G20 needles, respectively. The data points are colored according to the impact velocity, as indicated by the color scale.



becomes zero at a certain moment. In this experiment, a correction coefficient, C_{sen} , was determined based on this change of
 255 the momentum. The normal component of the impulse obtained from measurements, I_{meas} , can be expressed as

$$I_{meas} = \int F_{meas} dt = \int C_{sen} p_{meas} A_{sen} dt \quad (7)$$

where F_{meas} is the measured impact force, $p_{meas} = 1.35 \times 10^6 V_p$ is the measured pressure (average pressure on the sensing
 surface) in Pa, which is calculated from the sensitivity of 0.743 mV/kPa, V_p is the measured pressure in voltage, C_{sen} is a
 correction coefficient for non-uniform loadings, and A_{sen} is the sensing area of the sensor. Ideally, the integration interval in
 260 Eq. (7) should extend from the onset of the pressure rise to infinity. However, when applying this equation to the experimental
 data, the integration was performed up to the end of the measurement period, which was sufficiently long for the pressure
 to decay close to zero (see the figures in the appendix). A value of $C_{sen} = 1$ indicates no distortion of the sensor output due
 to partial loading, and if $C_{sen} < 1$, the sensor overestimates the pressure relative to the true pressure value. I_{meas} can also be
 expressed as

$$265 \quad I_{meas} = M_{ini} - M_{fin} = mV \quad (8)$$

where M_{ini} is the initial momentum before impact, $M_{fin} = 0$ is the momentum when the impacting droplet spreads and the
 velocity component normal to the impact surface becomes zero, and m is the droplet mass. The average droplet mass for each
 needle, which is calculated from the mean droplet diameter presented in Table 4, is used as the value of m . C_{sen} is considered
 a time-independent value; in other words, it represents the average value during impact. Therefore, by equating Eq. (7) and
 270 Eq. (8), C_{sen} can be expressed as follows:

$$C_{sen} = \frac{mV}{A_{sen} \int p_{meas} dt}. \quad (9)$$

The present experimental conditions lie within the frequency limit of the pressure sensor. The sensitivity of the pressure
 sensor increases significantly near its resonance frequency, and therefore the use at frequencies well below resonance is rec-
 ommended. Since the exact resonance frequency is not provided in the datasheet, the sensor response to signals at different
 275 frequencies was examined in Fig. 8 showing the relationship between the correction coefficient C_{sen} and the rise time to the
 peak impact force T_{peak} . In the figure, a reduction in C_{sen} , which would occur due to an increase in sensitivity, is not observed,
 although the output variation increases with decreasing T_{peak} .

Figure 9 shows the rise time to the peak impact force for each measurement data. For comparison, reference values for
 low-speed droplet impacts reported in previous studies (Cheng et al., 2022) are also included. The relationship between impact
 280 velocity and rise time is captured for the cases using the G32, G27, and G20 needles with the RET system. Although some
 scatter is present in the measurements, the figure clearly shows that the rise time decreases as the impact velocity increases. In
 these three cases, the rise times are generally shorter than the reference values. This is attributed to droplet deformation caused

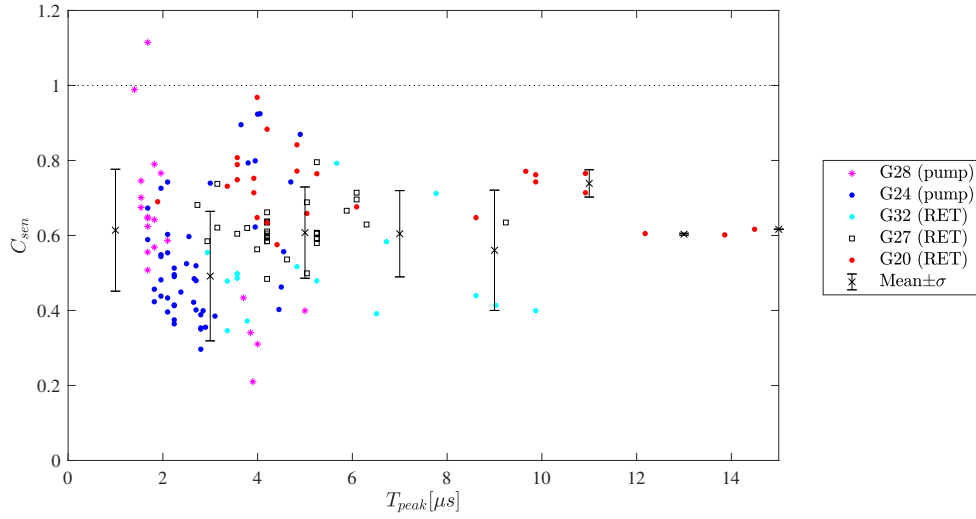


Figure 8. Relationship between the correction coefficient of the pressure sensor for non-uniform loadings C_{sen} and the time to the peak impact force T_{peak} presented for the cases with different needles. The black cross markers indicate the mean values, and error bars represent the values of $\pm$ standard deviation for each bin with a width of 2 μs .

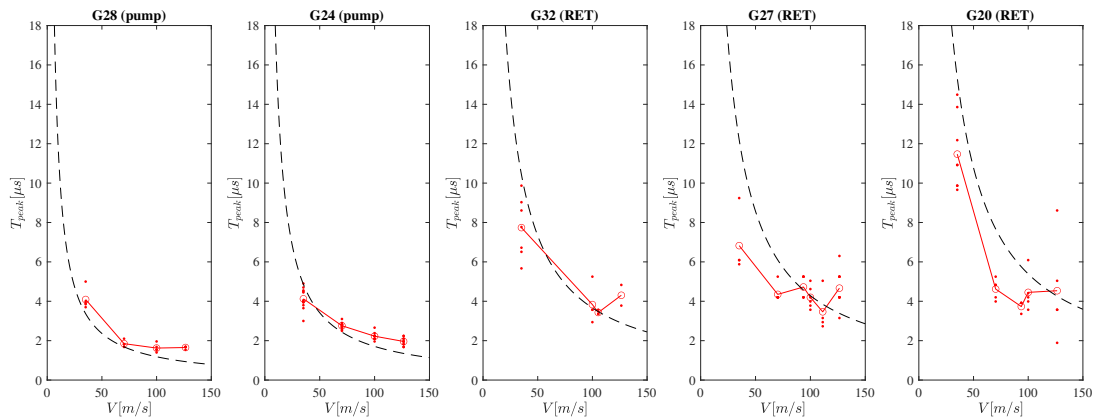


Figure 9. Relationship between impact velocity and rise time of the impact force for each needle used. The points represent individual measurements, while the circular markers connected by solid lines indicate the mean values for each impact velocity. The black dashed lines represent the rise time corresponding to the dimensionless peak time $T_{peak}V/D = 0.17$, the value of which is referred to Cheng et al. (2022).

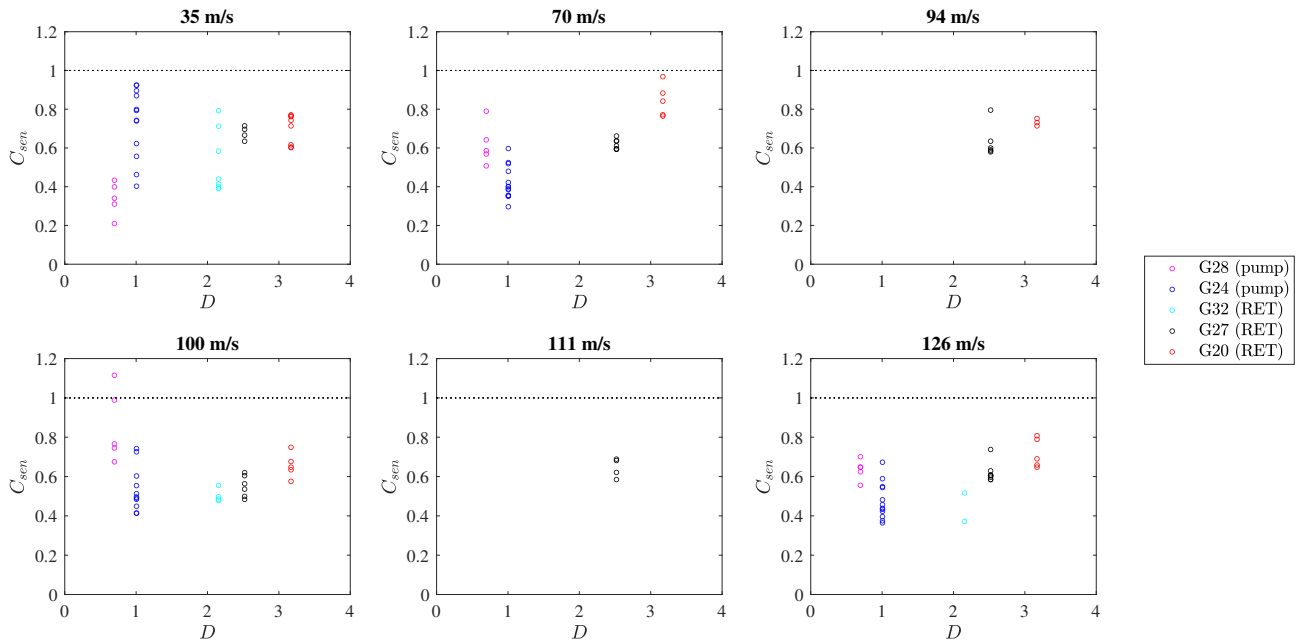


Figure 10. Correction coefficient of the pressure sensor for non-uniform loadings, C_{sen} , which is defined in Eq. (9), presented for each impact velocity.

by the high-speed airflow immediately before impact which allows the impact force to reach its peak faster than in the case of a spherical droplet. The scatter in the measurement data is considered to arise from variations in individual droplet diameters and differences in the manner of aerodynamic deformation. Time histories of the impact force for all measurement data are provided in Fig. A1, Fig. A2, and Fig. A3, from which illustrate the scatter in the rise time.

Regarding the response capability of the pressure sensor for rise time measurements, the present experiments are considered to satisfy the required threshold. For the G28 and G24 needles used with the tubing pump, the rise times are generally shorter because of the smaller droplet diameters. Although these values are close to the possible upper limit of the pressure sensor response and tend to be higher than the reference rise times, the decrease in rise time with increasing impact velocity is still captured correctly. Since the rise times for the three needle cases with the RET system are longer than those for the other two cases due to larger droplet diameter, the effect of the pressure sensor limitation is considered negligible in these measurements.

The calculated coefficients C_{sen} are shown in Fig. 10. The figure indicates that the values of C_{sen} were less than 1 for most of the data points. Moreover, comparison of each plot indicates no noticeable dependence of C_{sen} on the impact velocity. For the measurement data obtained using needles G28 and G24 from the tubing pump, the large deviations of the droplet diameter from the mean values, as shown in Table 4, cause the scatter in C_{sen} . Therefore, the mean value of $C_{sen} = 0.61$ derived from

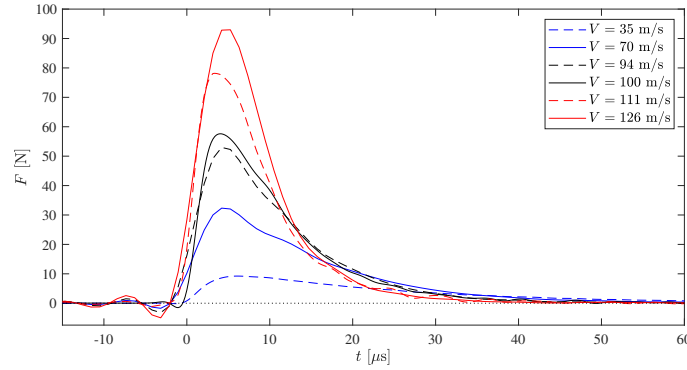


Figure 11. Averaged time histories of the impact force measured using the G27 needle for each impact velocity.

the data using G32, G27, and G20 needles with the RET water system was used to correct the calibration value of the pressure sensor.

In some cases, the impacting droplet may rebound from the surface, in which case the relation I_{meas} no longer holds. However, in our CFD simulations reproducing the experimental conditions, no droplet rebound was observed; therefore, this effect was not considered here.

Figure 11 shows the averaged time histories of the measured impact forces for different impact velocities. The original data before averaging are presented in Fig. A2. It indicates that the force peak increases as the impact velocity increases. The amplitude of the force peak for $V = 126$ m/s is 93 N. This corresponds to an average impact pressure of 4 MPa on the sensor surface with a surface area of 24.1 mm². In a previous study (Fujisawa et al., 2024), the impact pressure was reported as 18 MPa for nearly the same impact velocity and droplet diameter; however, their values are inconsistent with our measurements. This reason remains unclear, as their experimental conditions were not described in detail.

3.2 Numerical results

Further, we examined the impact force using a CFD model that assumes an ideal spherical droplet. First, we focused on the surface pressure distribution that constitutes the impact force. As shown in Fig. 12, the surface pressure scaled with the dynamic pressure ρV^2 for all presented cases lies on the same curve with small discrepancies. Additionally, the diameter of the pressure-induced area was scaled approximately with D for all cases, indicating that the contact area at the force peak was determined by the droplet diameter. The impact force reaches its maximum when half of the droplet volume collides with the surface. This is evident from a geometrical perspective. Consider the impulse equation, $F \Delta t = \Delta m V$, where Δm is a droplet mass colliding with the surface during infinitesimal time Δt . The force F reaches its maximum when Δm is at maximum, which occurs at the moment when half of the droplet volume collides with the surface. Therefore, the scaling of the pressure-induced area with D was reasonable. It can also be inferred from Fig. 12 that the lateral flow of the liquid does not significantly affect the dimension of the pressure-excited area. At maximum force, the lower hemisphere collided with the wall, with part of it flowing laterally

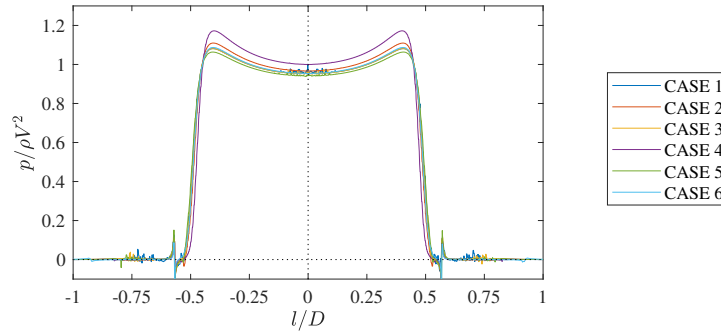


Figure 12. Surface pressure along the center line at the time of the force peak obtained by the CFD model for the six cases. The distance l on the horizontal axis and pressure p on the vertical axis are normalized with D and ρV^2 , respectively.

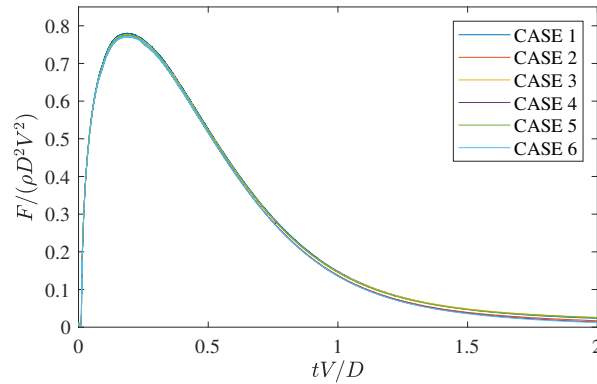


Figure 13. Time histories of the normalized impact force obtained by the CFD model for six cases.

as a side jet. The fact that the pressure-excited area depends on D indicates that this behavior is not influenced by deformation
 320 from the spherical shape due to droplet impact, that is, by the diameter of the droplet splashing. The findings that both the
 magnitude of the surface pressure and the spatial extent of the pressure-excited region at the time of the force peak can be
 scaled using ρ , D , and V , show that the peak impact force, obtained by integrating the surface pressure over the area, can also
 be non-dimensionalized using these parameters.

We observed the scaling of the surface pressure and, consequently, the scaling of the peak impact force, as shown in Fig. 12.
 325 Figure 13 shows the time history of the impact force obtained using the CFD model. The normalized forces in the six cases
 converge into a single curve. Thus, the scaling of the impact force holds throughout the duration from the moment of impact
 to its decay. The mean value of the normalized force peak is 0.78, which is consistent with the results of previous studies
 (Gordillo et al., 2018; Zhang et al., 2017). Since a high water-hammer pressure is generated immediately after droplet impact,
 accurately resolving the surface pressure distribution at the very early stage of impact would require a compressible-flow

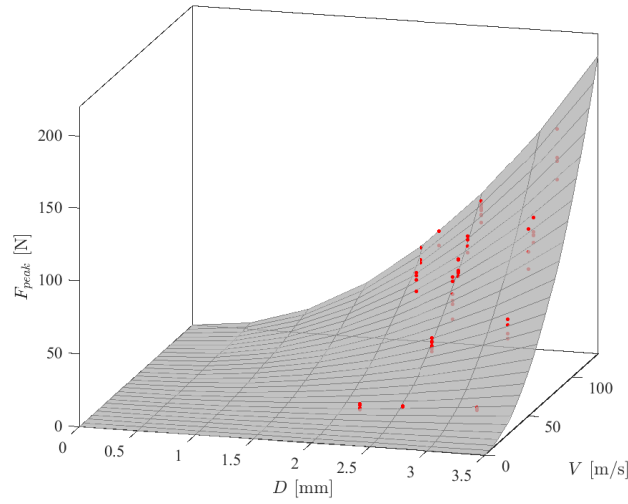


Figure 14. Measured peak impact force F_{peak} as a function of the droplet diameter and impact velocity (red markers) and the fitted surface expressed by $F_{peak_fit} = \rho C_0 D^2 V^2$ where $C_0 = 0.99$.

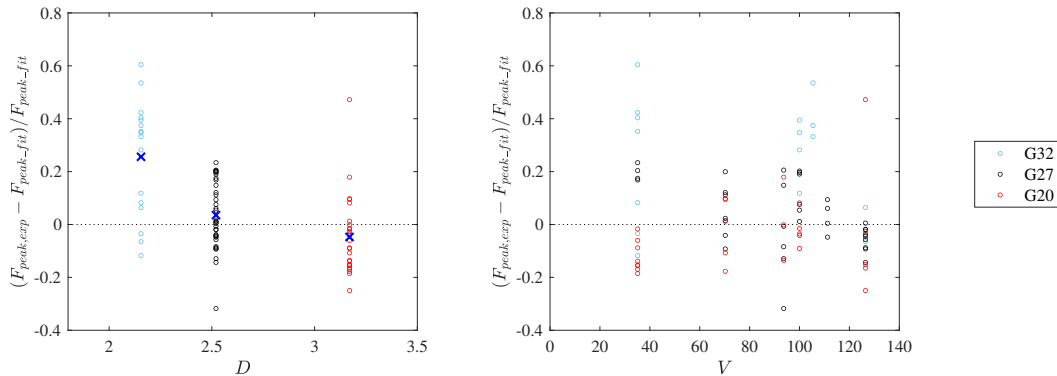


Figure 15. Deviations of the measured peak impact force $F_{peak,exp}$ from the value of the fitted surface expressed by $F_{peak_fit} = 0.99 \rho D^2 V^2$ for each measurement data. The left and right plots show the dependency of deviations on the droplet diameter and the impact velocity, respectively. Blue cross markers in the left plot show the average values for each of three droplet diameters.

330 model. However, assuming that liquid compressibility have a negligible effect on the overall droplet impact and spreading behavior, all simulations were conducted using the incompressible-flow model.



3.3 Comparison and discssion of experimental and numerical results

Figure 13 showed that the scaling of the impact force was valid at all times, but in the following discussion, we focus on the peak impact force as a representative moment. All the measurement data for the peak impact force were applied to the scaling equation. In other words, using a force coefficient C_0 , the peak impact force F_{peak} can be expressed as

$$F_{peak} = \rho C_0 D^2 V^2. \quad (10)$$

The values of C_0 for measurements and simulations, calculated using the least mean square method, were 0.99 and 0.77, respectively. The coefficients of determination denoted R^2 were 0.902 and 1.000, respectively. The measurement data and fitted surface using this C_0 value are shown in Fig. 14, suggesting that measurements follow the overall curve. The scaling of the impact force by V^2 can be explained by considering the portion of the liquid that collides normally with the flat wall over an infinitesimal time interval. Consider a thin disk-shaped segment of the droplet, with diameter d and thickness Δl , impacting the wall during an infinitesimal time Δt . Assuming no rebound, the impulse imparted by this infinitesimal volume element can be expressed as $F \Delta t = \Delta m V = 0.25 \pi \rho d^2 \Delta l (\Delta l / \Delta t)$, and the force becomes $F = 0.785 \rho d^2 (\Delta l / \Delta t)^2$. In reality, a liquid has previously collided with the wall when this portion of the droplet is impacting. However, the explanation from the experimental and numerical results that the force is proportional to the square of the impact velocity, i.e., $(\Delta l / \Delta t)^2$, indicates that the effect of water viscosity is negligible, and the force is applied to the wall at the original impact velocity.

Although C_0 values for the measurements and simulations were close to the value reported in previous studies, that is, approximately 0.8 or the theoretical value of 0.785 derived above, our measurements represented a slightly higher C_0 . As shown in Fig. 7, many droplets in the G32 and G27 cases exhibited flattened shapes, and such droplets dominate the overall measurement dataset. In general, a flattened droplets produces higher peak impact forces with shorter rise time than a spherical droplet, when comparing droplets of the same volume. This is because the volume of liquid impacting the wall per unit time is larger in the former case, leading to the higher and earlier peak impact force. This is because the temporal variation in the volume of liquid impacting the wall is larger in the flatten droplet, leading to the higher peak impact force with shorter time to the peak. Therefore, deformation from a spherical shape observed in measurements is considered to be one of the reasons for the increased value of C_0 .

To examine Fig. 14 in more detail, Fig. 15 plots the deviations of the measured impact force from the fitted surface as a function of droplet diameter and impact velocity. From the scatter and mean values of the data points in the left plot, it can be seen that the impact forces for the G32 needle are relatively higher than those for the G20 needle, while those for the G27 needle exhibit intermediate behavior. As described in Fig. 7, droplets generated by the G32 needle tended to flatten against the pressure sensor surface, whereas those generated by the G20 needle had approximately equal dimensions in all three directions. Flatten droplets causes higher peak impact force, and the present experimental results are consistent with the relationship between droplet shape and peak impact force. While Fig. 6 indicates the dependency of droplet shapes on the impact velocity for the G27 needle case, no clear relationship between the impact velocity and the deviation in impact force is observed in the right plots of Fig. 15.



365 4 Conclusions

This study investigated the impact force of medium-speed droplet collisions on wind turbine blades under conditions representative of rainfall erosion. Although actual wind turbine blades are composed of FRP and exhibit elastic behavior, the present study focuses on droplet impact on a rigid body. To this end, a rain erosion tester was used to reproduce droplet impacts at velocities ranging from 35 to 126 m/s. Using needles of different sizes, droplets with diameters ranging from approximately 1
370 to 3 mm were generated. The impact force when a single droplet collided with the leading edge of the rapidly rotating blade was measured using a pressure sensor. Droplet impacts produced a concentrated point load rather than a uniformly distributed surface load on the pressure sensor, potentially causing deformation of the sensor diaphragm and affecting output signals. Therefore, the sensor voltage output was calibrated using known droplet momentum values. CFD simulations for incompressible flows reproducing experimental conditions were conducted to calculate the impact force. Numerical results showed that
375 the surface pressure and pressure-excited area, both of which determine the impact force, were scaled with the dynamic pressure ρV^2 and droplet diameter D at the moment of the maximum impact force. As the simulations can model the collision of an ideally spherical droplet, the impact force followed the scaling of $\rho D^2 V^2$. Generally, the measured impact force fitted this scaling relationship, but they were slightly higher than those simulated. In terms of the force coefficient defined as the constant in the scaling relationship, the measurement value was 28% higher than the CFD value. High-speed camera images of the
380 droplets revealed that they undergo significant deformation just prior to impact due to the high-speed airflow around the blade. Specifically, the droplets tend to adopt a flattened shape relative to the pressure sensor surface. This deformation is considered to result in higher impact forces compared to those of spherical droplets. Therefore, to accurately obtain the peak impact force at relatively high impact velocities, the actual three-dimensional shape of the droplet under aerodynamic influences should be considered. Although the deformed shape of droplets impacting at medium speeds could not be precisely captured in this study,
385 future work will focus on formulating the impact force considering the actual raindrop deformation on wind turbine blades, which will contribute to accurate predictions of erosion damage on the blades.

Appendix A: Time histories of the impact force for all measurement data

Figure A1, Fig. A2, and Fig. A3 show the normalized impact forces for each impact velocity in the cases using the G32, G27, and G20 needles with the RET water system, respectively. It can be seen that even under the same needle and impact velocity
390 conditions, variations exist in both the peak impact force and the rise time to the peak.

Data availability. The experimental and CFD data supporting the findings of this study will be made publicly available upon acceptance of the manuscript. The DOI will be provided in the final version of the manuscript.

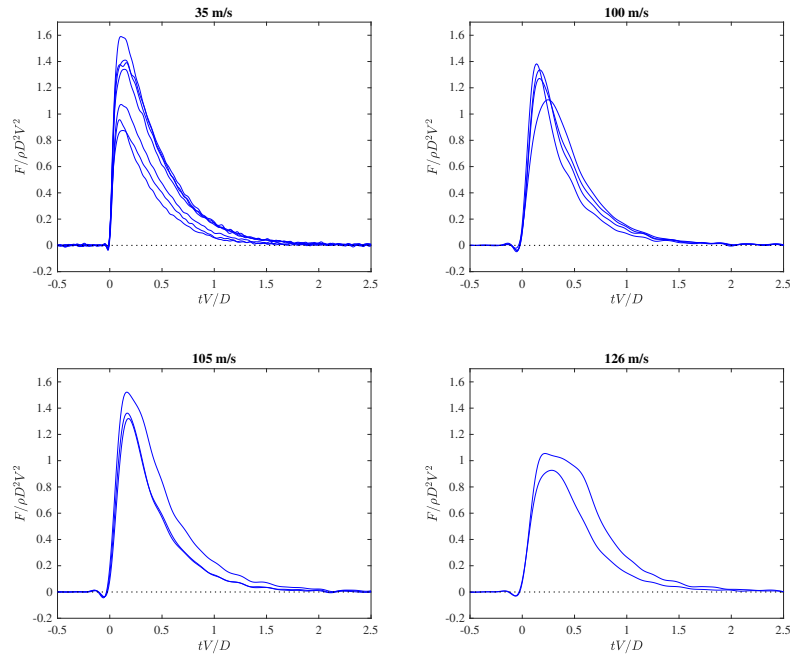


Figure A1. Time histories of the normalized impact force obtained from measurements using the G32 needle presented for each impact velocity.

Author contributions. AA conducted the experiments, performed the CFD simulations, and wrote the original manuscript. MT supervised the work, reviewed the manuscript, and was responsible for funding.

395 *Competing interests.* The contact author has declared that none of the authors has any competing interests.

Acknowledgements. We would like to thank K. Sakurai for assistance with the experiments. This study is based on results obtained from both a project, JPNP20005, commissioned by the New Energy and Industrial Technology Development Organization (NEDO) and a project of Fukushima prefecture, "Establishment of a Hub for Technology and Human Resource Development on Improved Operation and Maintenance of Wind Power Generation." Further, this research was conducted using the FUJITSU Supercomputer PRIMEHPC FX1000 and FUJITSU
 400 Server PRIMERGY GX2570 (Wisteria/BDEC-01) at the Information Technology Center, The University of Tokyo.

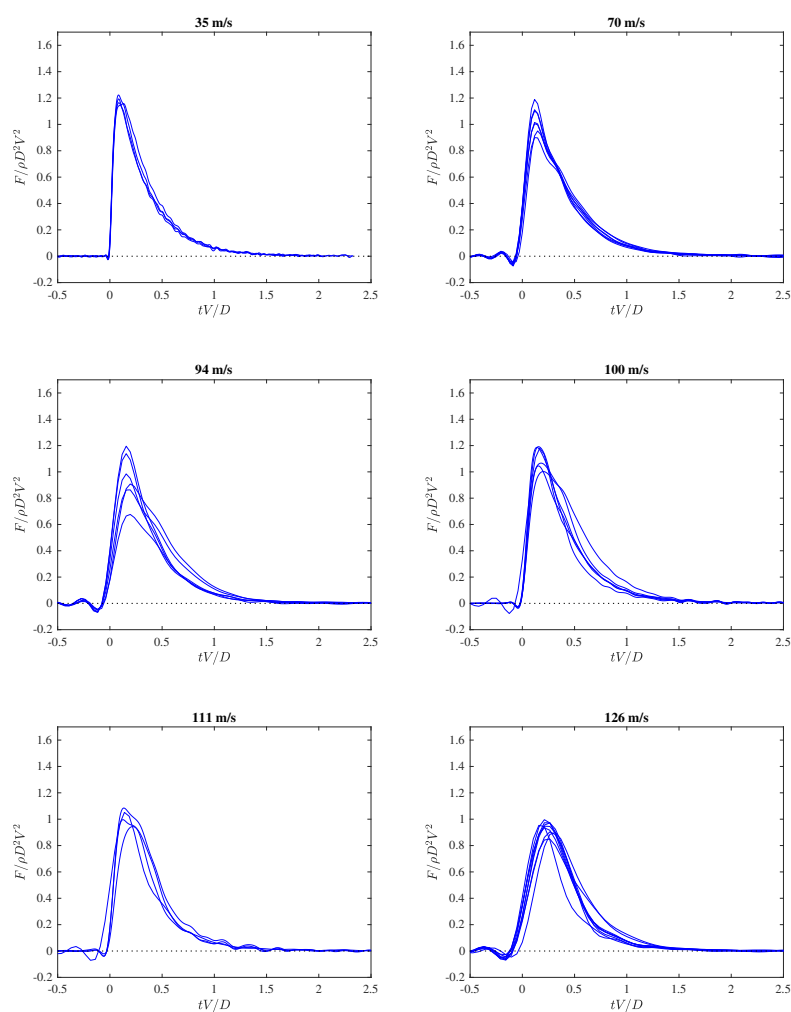


Figure A2. Time histories of the normalized impact force obtained from measurements using the G27 needle presented for each impact velocity.

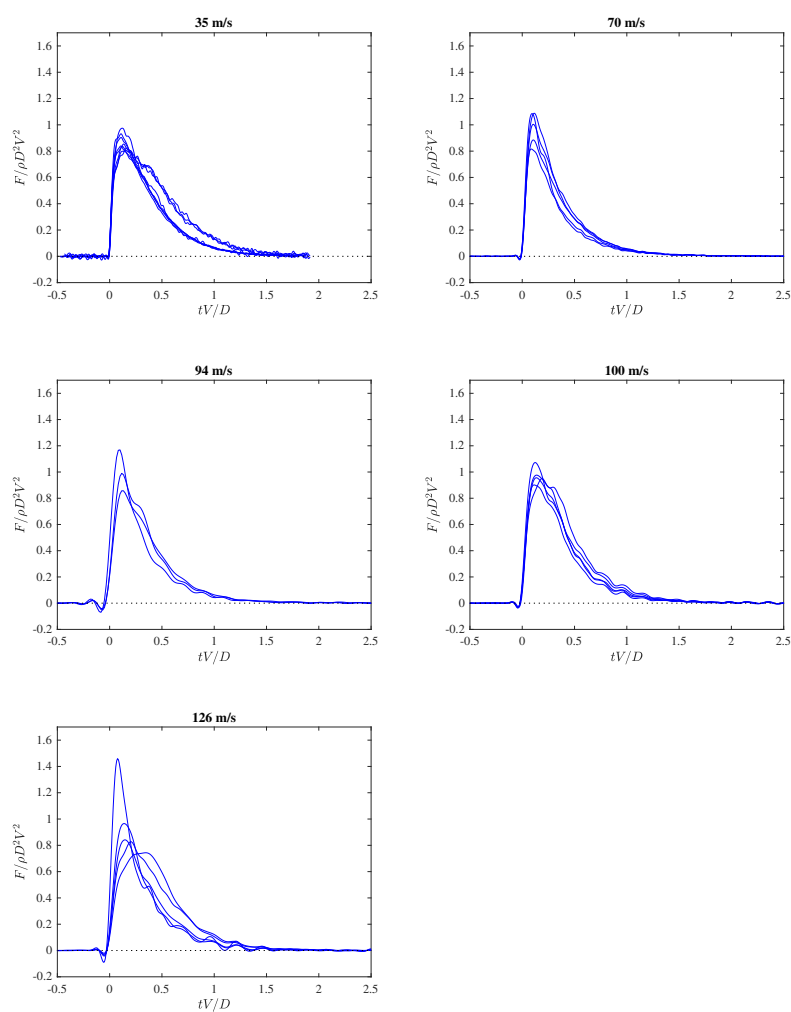


Figure A3. Time histories of the normalized impact force obtained from measurements using the G20 needle presented for each impact velocity.



References

- Aihara, A., Tanaka, M., and Fujisawa, N.: Influence of surface curvature on the impact force of water droplet, *Journal of Applied Physics*, 136, 114 701, <https://doi.org/10.1063/5.0219757>, 2024.
- Amirzadeh, B., Louhghalam, A., Raessi, M., and Tootkaboni, M.: A computational framework for the analysis of rain-induced erosion
 405 in wind turbine blades, part I: Stochastic rain texture model and drop impact simulations, *Journal of Wind Engineering and Industrial Aerodynamics*, 163, 33–43, <https://doi.org/10.1016/j.jweia.2016.12.006>, 2017a.
- Amirzadeh, B., Louhghalam, A., Raessi, M., and Tootkaboni, M.: A computational framework for the analysis of rain-induced erosion in wind turbine blades, part II: Drop impact-induced stresses and blade coating fatigue life, *Journal of Wind Engineering and Industrial Aerodynamics*, 163, 44–54, <https://doi.org/10.1016/j.jweia.2016.12.007>, 2017b.
- 410 Barfknecht, N. and von Terzi, D.: Aerodynamic interaction of rain and wind turbine blades: the significance of droplet slowdown and deformation for leading-edge erosion, *Wind Energy Science*, 9, 2333–2357, <https://doi.org/10.5194/wes-9-2333-2024>, 2024.
- Barfknecht, N. and von Terzi, D.: Drop-size-dependent effects in leading-edge rain erosion and their impact on erosion-safe mode operation, *Wind Energy Science*, 10, 315–346, <https://doi.org/10.5194/wes-10-315-2025>, 2025.
- Bech, J. I., Hasager, C. B., and Bak, C.: Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme
 415 precipitation events, *Wind Energy Science*, 3, 729–748, <https://doi.org/10.5194/wes-3-729-2018>, 2018.
- Bech, J. I., Johansen, N. F.-J., Madsen, M. B., Åsta Hannesd-Åstir, and Hasager, C. B.: 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>, 2022.
- Cheng, X., Sun, T.-P., and Gordillo, L.: Drop Impact Dynamics: Impact Force and Stress Distributions, *Annu. Rev. Fluid Mech.*, 54, 57–81,
 420 <https://doi.org/10.1146/annurev-fluid-030321-103941>, 2022.
- Cook, S. S.: Erosion by water-hammer, *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 119, 481–488, <https://doi.org/10.1098/rspa.1928.0107>, 1928.
- Cortés, E., Sánchez, F., O’Carroll, A., Madramany, B., Hardiman, M., and Young, T. M.: On the Material Characterisation of Wind Turbine Blade Coatings: The Effect of Interphase Coating–Laminate Adhesion on Rain Erosion Performance, *Materials*, 10,
 425 <https://doi.org/10.3390/ma10101146>, 2017.
- De Haller, P.: Untersuchungen über die durch Kavitation hervorgerufenen Korrosionen, *Schweiz. Bauztg.*, 101, 243, 1933.
- Eisenberg, D., Laustsen, S., and Stege, J.: Wind turbine blade coating leading edge rain erosion model: Development and validation, *Wind Energy*, 21, 942–951, <https://doi.org/10.1002/we.2200>, 2018.
- Engel, O. G.: Waterdrop collisions with solid surfaces, *Journal of research of the national bureau of standards*, 54, 281–298,
 430 <https://doi.org/10.6028/JRES.054.033>, 1955.
- Field, J., Dear, J., and Ogren, J.: The effects of target compliance on liquid drop impact, *Journal of Applied Physics*, 65, 533–540, <https://doi.org/10.1063/1.343136>, 1989.
- Field, J. E., Lesser, M. B., and Dear, J.: Studies of two-dimensional liquid-wedge impact and their relevance to liquid-drop impact problems, *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, 401, 225–249,
 435 <https://doi.org/10.1098/rspa.1985.0096>, 1985.
- Fujisawa, N., Yoshida, M., and Yamagata, T.: Experimental Method for Measuring the Impact Force of a Rain Droplet on the Leading Edge of a Wind Turbine Blade, *Journal of Flow and Energy*, 2, 37–46, https://doi.org/10.60197/flowenergy.2.0_37, 2024.



- Gordillo, L., Sun, T.-P., and Cheng, X.: Dynamics of drop impact on solid surfaces: evolution of impact force and self-similar spreading, *J. Fluid Mech.*, 840, 190–214, <https://doi.org/10.1017/jfm.2017.901>, 2018.
- 440 Hasager, C., Vejen, F., Bech, J., Skrzypinski, W., Tilg, A.-M., and Nielsen, M.: Assessment of the rain and wind climate with focus on wind turbine blade leading edge erosion rate and expected lifetime in Danish Seas, *Renewable Energy*, 149, 91–102, <https://doi.org/10.1016/j.renene.2019.12.043>, 2020.
- Herring, R., Dyer, K., Martin, F., and Ward, C.: The increasing importance of leading edge erosion and a review of existing protection solutions, *Renewable and Sustainable Energy Reviews*, 115, 109 382, <https://doi.org/10.1016/j.rser.2019.109382>, 2019.
- 445 Heymann, F. J.: High-speed impact between a liquid drop and a solid surface, *Journal of Applied Physics*, 40, 5113–5122, <https://doi.org/10.1063/1.1657361>, 1969.
- Hirt, C. and Nichols, B.: Volume of fluid (VOF) method for the dynamics of free boundaries, *Journal of Computational Physics*, 39, 201–225, [https://doi.org/10.1016/0021-9991\(81\)90145-5](https://doi.org/10.1016/0021-9991(81)90145-5), 1981.
- Hoksbergen, T., Akkerman, R., and Baran, I.: Rain droplet impact stress analysis for leading edge protection coating systems for wind turbine
- 450 blades, *Renewable Energy*, 218, 119 328, <https://doi.org/https://doi.org/10.1016/j.renene.2023.119328>, 2023.
- Jones, S. M., Rehfeld, N., Schreiner, C., and Dyer, K.: The Development of a Novel Thin Film Test Method to Evaluate the Rain Erosion Resistance of Polyaspartate-Based Leading Edge Protection Coatings, *Coatings*, 13, <https://doi.org/10.3390/coatings13111849>, 2023.
- Katsivalis, I., Chanteli, A., Finnegan, W., and Young, T. M.: Mechanical and interfacial characterisation of leading-edge protection materials for wind turbine blade applications, *Wind Energy*, 25, 1758–1774, <https://doi.org/https://doi.org/10.1002/we.2767>, 2022.
- 455 Li, J., Zhang, B., Guo, P., and Lv, Q.: Impact force of a low speed water droplet colliding on a solid surface, *J. Appl. Phys.*, 116, 214 903, <https://doi.org/10.1063/1.4903316>, 2014.
- Li, R., Ninokata, H., and Mori, M.: A numerical study of impact force caused by liquid droplet impingement onto a rigid wall, *Progress in Nuclear Energy*, 53, 881–885, <https://doi.org/10.1016/j.pnucene.2011.03.002>, 2011.
- Miner, M. A.: Cumulative Damage in Fatigue, *Journal of Applied Mechanics*, 12, A159–A164, <https://doi.org/10.1115/1.4009458>, 1945.
- 460 Mitchell, B., Nassiri, A., Locke, M., Klewicki, J., Korkolis, Y., and Kinsey, B.: Experimental and numerical framework for study of low velocity water droplet impact dynamics, in: *International Manufacturing Science and Engineering Conference*, vol. 49897, p. V001T02A047, American Society of Mechanical Engineers, 2016.
- Panthi, K. and Iungo, G. V.: Quantification of wind turbine energy loss due to leading-edge erosion through infrared-camera imaging, numerical simulations, and assessment against SCADA and meteorological data, *Wind Energy*, 26, 266–282, <https://doi.org/https://doi.org/10.1002/we.2798>, 2023.
- 465 Rusche, H.: Computational fluid dynamics of dispersed two-phase flows at high phase fractions, <http://hdl.handle.net/10044/1/8110>, 2003.
- Sareen, A., Sapre, C. A., and Selig, M. S.: Effects of leading edge erosion on wind turbine blade performance, *Wind Energy*, 17, 1531–1542, <https://doi.org/https://doi.org/10.1002/we.1649>, 2014.
- Slot, H. et al.: Review on droplet impact erosion modeling and experimental validation for coated wind turbine blades, *Renewable Energy*,
- 470 80, 837–848, <https://doi.org/10.1016/j.renene.2014.12.012>, 2015.
- Soto, D., De Larivière, A. B., Boutillon, X., Clanet, C., and Quéré, D.: The force of impacting rain, *Soft Matter*, 10, 4929–4934, <https://doi.org/10.1039/c4sm00513a>, 2014.
- Springer, G.: *Erosion by Liquid Impact*, (A Halsted Press book), Scripta Publishing Company, ISBN 9780470151082, 1976.
- Tempelis, A., Jespersen, K. M., Dyer, K., Clack, A., and Mishnaevsky, L.: How leading edge roughness influences rain erosion of wind
- 475 turbine blades?, *Wear*, 552–553, 205 446, <https://doi.org/https://doi.org/10.1016/j.wear.2024.205446>, 2024.



- Zhang, B., Li, J., Guo, P., and Lv, Q.: Experimental studies on the effect of Reynolds and Weber numbers on the impact forces of low-speed droplets colliding with a solid surface, *Exp. Fluids*, 58, <https://doi.org/10.1007/s00348-017-2413-z>, 2017.
- Zhou, Q., Li, N., Chen, X., Xu, T., Hui, S., and Zhang, D.: Analysis of water drop erosion on turbine blades based on a nonlinear liquid–solid impact model, *International Journal of Impact Engineering*, 36, 1156–1171, <https://doi.org/10.1016/j.ijimpeng.2009.02.007>, 2009.
- 480 Zhou, W., Zhang, D., and Yang, M.: Effects of surface curvature on rain erosion of wind turbine blades under high-velocity impact, *Heliyon*, 10, <https://doi.org/10.1016/j.heliyon.2024.e40761>, 2024.