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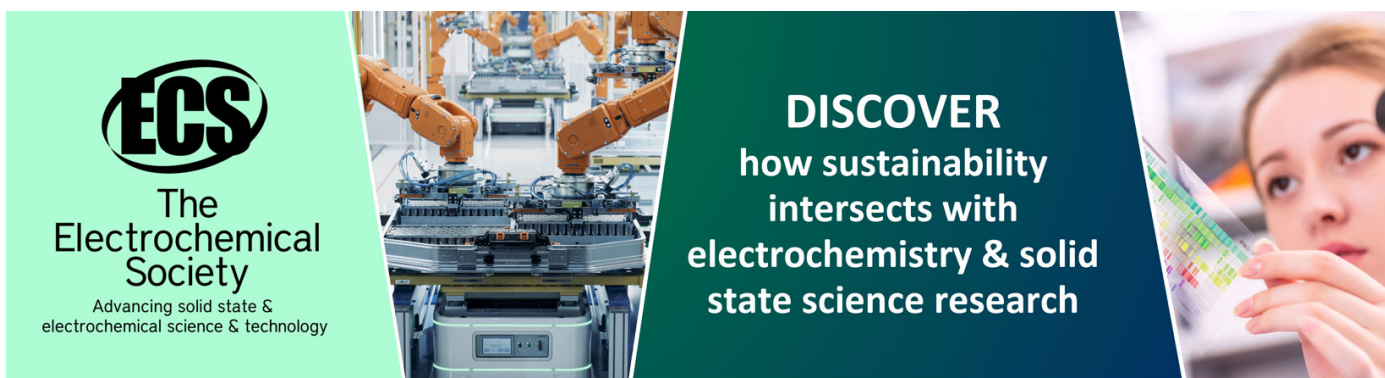
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Effects of hydrometeor droplet characteristics on wind turbine blade leading edge erosion: A numerical study

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Abstract. Leading edge erosion of wind turbine blades is a significant source of loss of energy production in some wind farms. The extent of erosion appears to be controlled, at least in part by local meteorological conditions; specifically, by the accumulated kinetic energy transfer from collisions with falling hydrometeors (precipitation). However, the aerodynamics of flow around wind turbine blades means not all falling hydrometeors will impact the blade, and at least in principle some will be sufficiently small to follow the streamlines and thus avoid collisions with the rotating blades. Here we present the set-up for computational fluid dynamics (CFD) simulations designed to quantify collision efficiency as a function of hydrometeor size for a simplified three-blade turbine using ANSYS Fluent 19.2 as the main numerical solver. The simulations correctly reproduce the pressure variability across the blade and illustrate that the variations in the droplet-blade collision probability is a function of wind speed, rain intensity and droplet diameter.

1. Introduction

Loss of blade aerodynamic performance results from roughening of the blade edge either by removal of blade material or accretion of ice/insect debris [1-7]. This causes a reduction in the aerodynamic lift and thus the efficiency of wind turbines. Blade leading edge erosion (LEE) describes damage to (and materials removal from) the wind turbine blade leading edge. LEE can be generated by a variety of airborne particles, but research to date suggests materials stresses caused by impacts from precipitation (hydrometeors) are a major source of LEE [1]. The erosion is accelerated in the rotor tip region where the rotation speed is very high which means that the net closing velocity between falling hydrometeors and the rising wind turbine leading edge is highest. The high-speed rotor tip region is the most important part of the blade in optimum blade performance and accounts for more than 1/3 of the total energy capture [8, 9].

Leading-edge erosion has been observed in only after two years after commissioning, which is very early given that the turbines are expected to run over a time span of at least 20 years [10, 11]. Although advances have been made towards quantifying the damage of the blade from falling hydrometeors, understanding to what extent the roughness changes contribute to leading-edge erosion remains incomplete [12-15]. Without understanding the mechanisms that govern the collision probability and material responses to impacts from hydrometers or other abrasive aerodynamic particles, it is difficult to develop strategies to mitigate the issue, to predict the occurrence of LEE, to quantify and predict how much energy loss will occur for an operational wind turbine or to optimize a maintenance strategy. As



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a first step towards the formidable challenge of understanding the intricate connection between hydrometeors, blade aerodynamics, and blade leading edge erosion, the present work aims to build a set of 3D horizontal turbine blade system numerically and analyse the aerodynamic performance of the turbine blade, and establish a set of particle tracking systems in the turbine blade domain and examine the effects of rainfall intensity and size on the probability of particle collision with the blade.

2. Theoretical Background

2.1 Governing equations

The governing equations are based on the Navier-Stokes Equations in a multiple-reference coordinate system [16-18]. The turbulent model used to simulate the wind flow in the blade domain is based on the $k\sim\omega$ model. For a fixed stationary control volume, the conservation of mass gives,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \quad (1)$$

where t is the time, ρ is the air density, $\vec{u}$ is the velocity vector, p is the static pressure, and the operator $\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$ is the gradient sign. Conservation of momentum provides,

$$\frac{\partial(\rho \vec{u})}{\partial t} + \nabla \cdot \rho(\vec{u} \vec{u}) = -\nabla p + \nabla \cdot \bar{\tau} \quad (2)$$

where $\bar{\tau}$ is the shear stress vector given as

$$\bar{\tau} = \nu \left[(\nabla \vec{u} + \nabla \vec{u}^T) - \frac{2}{3} \nabla \cdot \vec{u} I \right] \quad (3)$$

where ν is kinetic viscosity and I is the unit tensor. Applying the above two equations to a rotating domain, the mass conservation equation becomes,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u}_r = 0 \quad (4)$$

and the equation of the conservation of momentum yields,

$$\frac{\partial(\rho \vec{u}_r)}{\partial t} + \nabla \cdot \rho(\vec{u}_r \vec{u}_r) + \rho(2\vec{\omega}_r \times \vec{u}_r + \vec{\omega}_r \times \vec{\omega}_r \times \vec{r}) = -\nabla p + \nabla \cdot \bar{\tau}_r \quad (5)$$

where r is the variable in the radius direction, $\vec{u}_r = \vec{u} - \vec{\omega}_r \times \vec{r}$ is the relative velocity (the velocity viewed from the moving frame) and $\vec{\omega}_r$ is the angular velocity, $(2\vec{\omega}_r \times \vec{r})$ is the Coriolis force and $(\vec{\omega}_r \times \vec{\omega}_r \times \vec{r})$ is the centripetal acceleration.

The stationary shear-stress transport (SST) $k\sim\omega$ model [19] is used for the wind turbulence simulation given its advantage in addressing the low-Reynolds number effects and shear flow spreading. The $k\sim\omega$ model is an empirical turbulent model based on the turbulent kinetic energy (k) and the dissipation rate (ω). The details of this model have been well described elsewhere [16-18].

Below the rain droplets are simulated by the discrete phase model (DPM), where the rain droplets are tracked in a Lagrangian reference frame. Note that the DPM is only valid for the domain when the volume fraction is lower than 10% so that the particle-particle interactions and the impact of the particle volume fraction on the fluid transport can be neglected. Particles in DPM are assumed to be spherical. The sphere is considered as a mass point with a known radius value R . The particles are injected over the inlet and the inlet top surfaces, with a specific predetermined velocity. Self-rotation of the particles, particle-particle interactions, particle-precipitation interactions and other turbulence-related phenomena [20-22] are assumed to be second order effects and are neglected in the current work.

2.2 Boundary conditions

The inflow free surface wind is represented with a constant velocity U . The outlet condition is the free pressure condition (the local pressure equals the free atmosphere pressure), where the outflow velocity is to be determined. The blade surface is assumed to be a rough wall, so that the no-slip boundary condition is applied, which is,

$$\vec{u}_r = 0 \quad (6)$$

The particles in the wind flow are given an initial velocity. The particle initial velocity is decomposed into two components, one in the vertical direction and the other in the horizontal direction. The horizontal component is the uniform inflow wind speed as stated. Over the range of hydrometeor radii (R) of 20 to 2500 μm , the vertical rain droplet falling velocity is given by Stull [23]:

$$V = -c \left[V_0 - \exp\left(\frac{R_0 - R}{R_1}\right) \right] \quad (7)$$

where the three parameters are given as $V_0 = 12\text{m/s}$, $R_0 = 2.5\text{mm}$ and $R_1 = 1\text{mm}$, according to Stull [23]. The parameter c is a density correction factor, which can be estimated using $c = \sqrt{70/p}$. Note that this equation is based on a balance between the gravitational forces and frictional drag.

Interactions between the particles and the blade can have three different scenarios (Figure 1): (a) the escape case: when the rain droplet bypasses the blade and follows its original streamline (b) the trap case: where the rain droplet is collected on the blade (c) the reflect case: when the rain droplet bounces off the blade surface and moves in a different direction. Since many particle and blade material properties that are required to compute reflection rates this is not considered in the present simulations. In this work we assume all hydrometeors are either fully captured by the blade or can avoid the blade (only (a) and (b) are considered) entirely due to hydrometeors being streamline following and not impacting the blade.

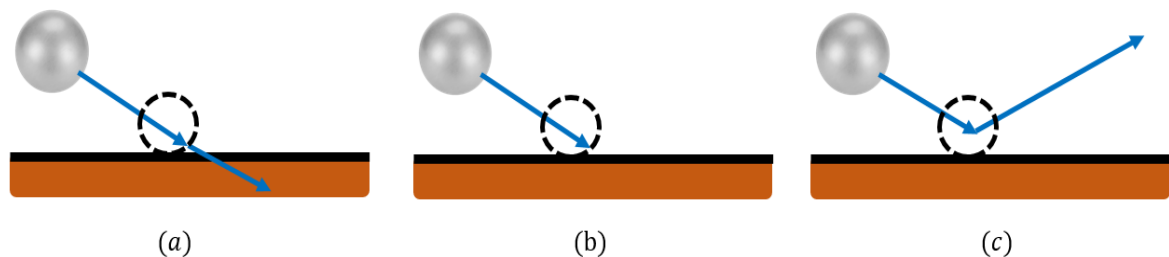


Figure 1. The interaction between particles and the blade surface. Three scenarios are assumed: (a) the escape case (b) the trap case and (c) the reflection case.

2.3 Numerical assumptions

Steady-state conditions are assumed for the wind turbine. Turbulence or thermal effects are not considered in current simulations; therefore, the air density is set as a constant. The turbine is assumed to have three identical blades. Flow is considered to be homogenous such that we can model 1/3 of the domain with one blade inside it. The blade is fixed in the midst of the domain and can only rotate along the z -axis in the YZ plane. The wake is non-rotating, and each point on the blade is considered to have the same angular velocity, which is used to ensure that the moving frame technique in ANSYS Fluent can be applied for the simulation. Finally, uniform thrust is assumed over the disc and the rotor area, so that the Navier-Stokes equations can be used to simulate the velocity and pressure fields of the fluid through the wind turbine.

3. Numerical setup

3.1 Domain configuration

As shown in Figure 2, the computational domain is set as a circular truncated cone (to reduce computational burden while maintain a good representation of the turbine system), where the blade is attached along the x direction in the origin. The conical shape is used to reduce the domain size while maintaining good accuracy of the calculation [24]. The wind flow is along the $(-z)$ direction with a uniform velocity of U . Two 2D side views of the domain and blade are also plotted in Figure 2.

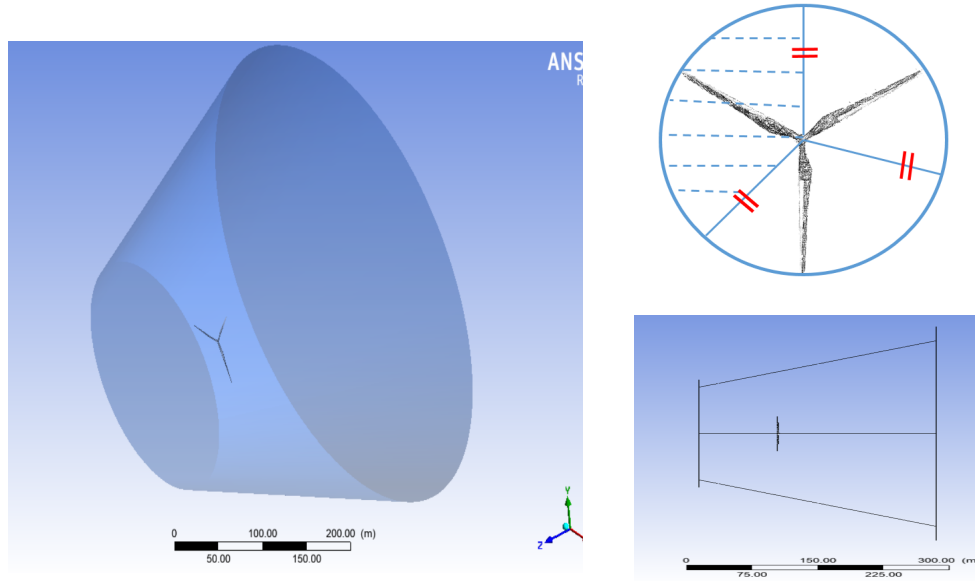


Figure 2. A 3D representation of the computational domain of the turbine blades and the two side views of the computational domain and the turbine blades. Only the shaded part is used in the computational simulations. The periodic condition is maintained on the two sides of the shaded area which are denoted with the “=” sign.

The inlet is set with a radius of 120 m, while the outlet is 240 m (Figure 2). These two surfaces are 270 m away from each other horizontally, where the blade is in the middle and set as the origin of this domain. The domain is the shaded area in Figure 2. The blade is set along the x-direction and the wind is coming in from the left circular surface in ($-z$) direction. Each of the three blades occupy the same space rotating with the same velocity, $\vec{\omega}_r$, therefore, only 1/3 of the entire domain is used in the numerical simulations to reduce the computational burden. Since we are only simulating 1/3 of the truncated circular cone, periodic conditions are used for the periodic walls 1 and 2. The periodic condition is expressed with the following equation:

$$\vec{u}_r(r_i, \theta) = \vec{u}_r(r_i, \theta - 120^\circ n) = 0 \quad (8)$$

with $n = 1, 2, 3 \dots$ where θ is the rotating angle. This equation indicates that the velocity profiles at the angle of $\theta = 0^\circ$, $\theta = 120^\circ$, $\theta = 240^\circ$ and $\theta = 360^\circ$ are the same. If we use θ_1 and θ_2 to represent the two periodic boundaries of the 1/3 domain, then we have the expression that $\vec{u}_r(r_i, \theta_1) = \vec{u}_r(r_i, \theta_2)$.

3.2 Mesh generation and blade configuration

The mesh is automatically generated in the ANSYS environment based on the optimized computational efficiency method considering the available cores and the parallel processing in the computer. To make the results more accurate near the blade, a refined mesh is used in a spherical region around the blade. The detail of the techniques used have been discussed elsewhere [16-18]. To ensure that a normal velocity of 80 ms^{-1} which is a typical tip velocity for the wind turbine, can be achieved near the blade tip, the blade is set as 43.2 m in length [16-18]. The root region of the blade is set as a cylindrical shape and transitions to airfoils S818, S825 and S826 for the root, the body and the tip regions, respectively. The blade has a pitch angle of 4 degrees at the tip and is twisted as a function of radius.

3.3 Particle simulations

The embedded DPM module [16,17] is employed for current particle investigations. The transport and fluid equations are not repeated here but can be found elsewhere, i.e. [16,17]. The wind and particle

injection in the computational domain is shown in Figure 3. In the simulations, the rain droplets are introduced at the top of the domain shown with the red arrows while the inflow velocity is horizontal shown with the black arrows.

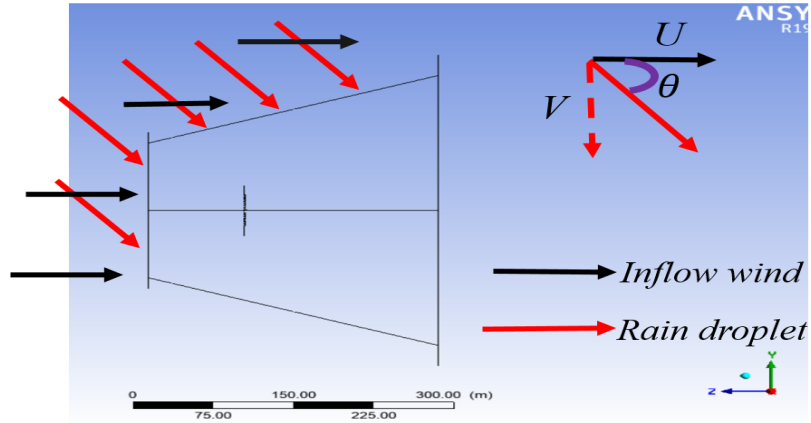


Figure 3. The computational domain and flow and particle directions. The red and black arrows represent the inflow wind and particle, respectively.

Particles in the simulations that represent rain droplets are assumed to be uniformly distributed over the entire domain and to have the same radius R . The median droplet radius is used for the simulations. Five different rain intensities are considered: 20mmh^{-1} , 40mmh^{-1} , 60mmh^{-1} , 80mmh^{-1} , 100mmh^{-1} . The model builds on the commonly accepted Marshall-Palmer rain droplet distribution function and an empirical rain intensity-droplet number relationship. The rain flux (Fx_R) for a specific rain intensity (RR) can be calculated using the mass flux equation,

$$Fx_R = \rho_p S_t RR \quad (9)$$

where ρ_p as defined is particle density, S_t is the surface area of the computational domain, which is perpendicular to the rain fall. This surface area can be estimated using,

$$S_t = \pi(R_1^2 + R_2^2)\cos\theta \quad (10)$$

where R_1 and R_2 are the radius of the left and right circular lateral surface of the computational domain as shown in Figure 3, θ is the angle between U and V . The angle θ can be calculated using the geometric relationship,

$$\cos\theta = \frac{U}{\sqrt{U^2 + V^2}} \quad (11)$$

For the rain droplet characterized radius, the median value, R_{50} value is used to represent the particle size ($R=R_{50}$). The R_{50} value is computed using the formula [25].

$$R_{50} = 1.635 - 0.816\exp(-0.04RR) \quad (12)$$

Equation 12 shows that when rain intensity increases, the R_{50} value also increases. Once the rainfall intensity is predetermined, a characteristic rain droplet radius (R_{50}) is assumed for all hydrometeors in the domain. The total number of hydrometeors in the domain can be calculated using the total volume of the rain in the domain over the volume of each rain droplet according to R_{50} values. For comparison, the radius range is also decreased and set ($R = R_{50}$) to about 15-20% of the R_{50} values to run an additional series of simulations.

The residual error arises from the discretization when the partial differential equations are approximated with a group of algebraic equations and every algebraic equation must be solved for an individual control volume. After running the simulation for 1500 iterations, the residual errors are less than 1×10^{-4} which is deemed sufficient to stop the iteration.

4. Results

4.1 Aerodynamic simulation results

Pressure contours on cross-sections at three representative locations; the near root region (at $x=-10\text{m}$), the near-tip region (at $x=-43\text{m}$), and the region between the tip and the root (blade mid-point, at $x=-35\text{m}$) are shown in Figure 4 and exhibit the expected spatial variability. Pressure is larger (i) in the leading-edge region than that in the trailing edge (ii) in the front of the blade than that in the back (iii) in the tip region than that in the root and mid regions. Velocity streamlines for the same cross-sections are shown in Figure 5. The simulations show that velocities are larger on the top surface of the airfoil than the bottom surface. This is expected, due to the pressure gradient around the blade.

4.2 Particle simulations

For the particle simulations, illustrative results are shown for an operational wind condition $U = 12\text{ms}^{-1}$ and five different rain intensities in Table 1. The results show the number of particles in the entire domain and the proportion that impact the blade (Trapped) for different rainfall rates and hence R_{50} values. The collision ratio (Ratio) is the percentage of particles in the domain that are trapped by the blades. Table 2 shows results for particles with a smaller radius (i.e. values of R_{s50}). This analysis was undertaken to examine rain droplet diameters near to values that have been suggested to represent the threshold ($R = 0.2\text{ mm}$) at which they have insufficient inertia to ensure impaction and may be deflected from the blade by streamline deformation [26].

Table 1. Simulation conditions and results for a range of raindrop radii (R_{50}) for $U = 12\text{ms}^{-1}$

RR mm/h	U m/s	R_{50} mm	V m/s	$\cos\theta$ -	S_t m^2	Fx_R kg/s	Total #/s	Trapped #/s	Ratio %
20	12	1.27	8.57	0.81	184044.37	1022.47	1.20E+08	7.35E+04	0.06%
40	12	1.47	9.20	0.79	179510.08	1994.56	1.50E+08	2.76E+05	0.18%
60	12	1.56	9.44	0.79	177759.82	2962.66	1.86E+08	2.29E+05	0.12%
80	12	1.60	9.54	0.78	177025.48	3933.90	2.29E+08	2.81E+05	0.12%
100	12	1.62	9.59	0.78	176705.53	4908.49	2.76E+08	3.39E+05	0.12%

Table 2: Simulation conditions and results for a range of raindrop radii (R_{s50}) for $U = 12\text{ms}^{-1}$

RR mm/h	U m/s	R_{s50} mm	V m/s	$\cos\theta$ -	S_t m^2	Fx_R kg/s	Total #/s	Trapped #/s	Ratio %
20	12	0.228	2.30	0.98	222140.17	1234.11	2.48E+10	4.57E+06	0.018%
40	12	0.231	2.33	0.98	222033.37	2467.04	4.75E+10	2.51E+07	0.053%
60	12	0.233	2.35	0.98	221989.72	3699.83	7.01E+10	4.05E+07	0.058%
80	12	0.235	2.37	0.98	221922.27	4931.61	9.11E+10	5.49E+07	0.060%
100	12	0.236	2.38	0.98	221888.41	6163.57	1.12E+11	6.91E+07	0.061%

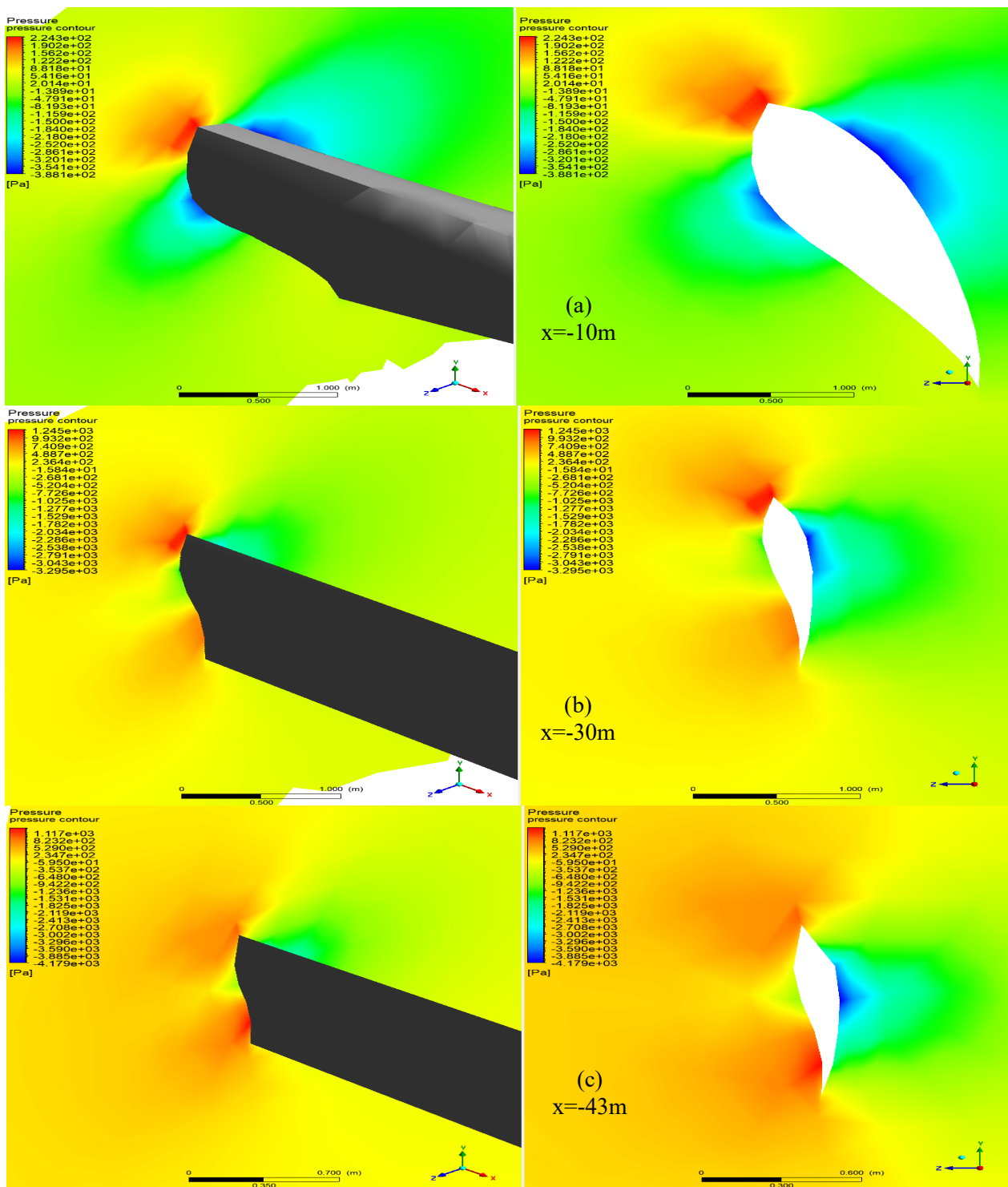


Figure 4. Pressure contours for the root, mid and tip regions respectively. Each plot shows the different shape of the airfoil at that section and the pressure in the selected plane.

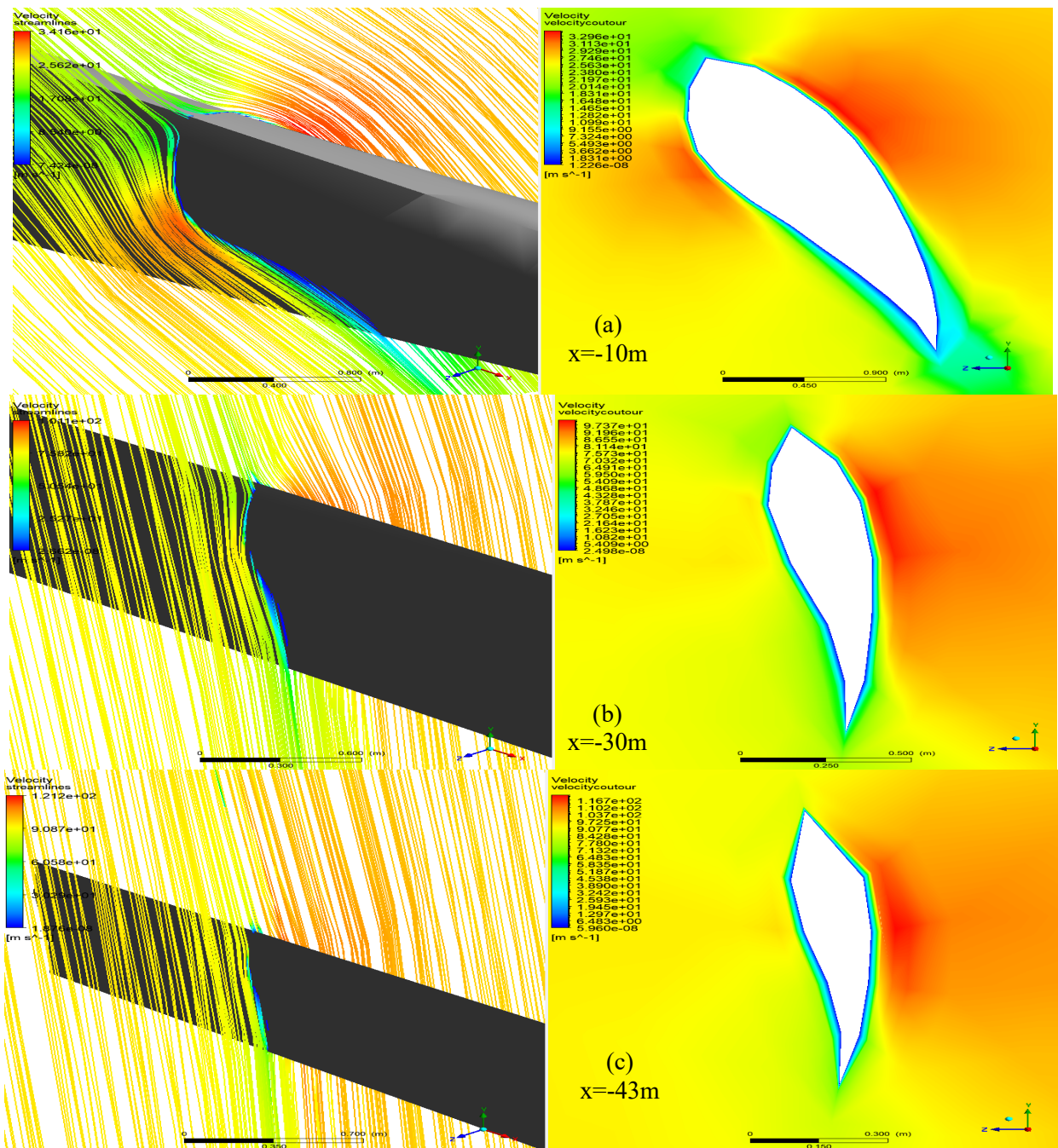


Figure 5. Fluid streamlines for the wind speed near the root, mid and tip regions. In each plot, the left-hand side shows the fluid streamlines around the blade. The right-hand side shows a 2D velocity contour on the selected plane.

Due to the low particle (rain droplet) concentrations that can be employed within DPM for tracking, geometric analyses indicate only a very small portion will interact with the blade ($\sim 0.16\%$). Thus, if the particles exhibited 100% collision efficiency for these simulations only 0.16% would be trapped by the blade. The experimental results indicate a maximum trapping efficiency of 0.18% for the 12 ms^{-1} wind speed case and a droplet radius of 1.47 mm (Figure 6). Consistent with expectations the trapping efficiency is approximately constant with rainfall rates since they primarily affect the number of droplets with only a modest impact on hydrometeor radii (recall for R_{50} the radii range considered is 1.27 and 1.62 mm). For R_{50} of 1.56 and 1.62 mm the trapping efficiency is 0.12% which is slightly lower than the expected values ($\sim 0.16\%$), while for R_{50} of 1.47 mm it is slightly above (0.18%). For the smaller particles (R_{50} : 0.228-0.236 mm), the efficiency of capture is approximately half that for the larger particles, consistent with *a priori* expectations that particles of this diameter are of a size at which they have sufficiently small inertia that they are at least partly streamline following.

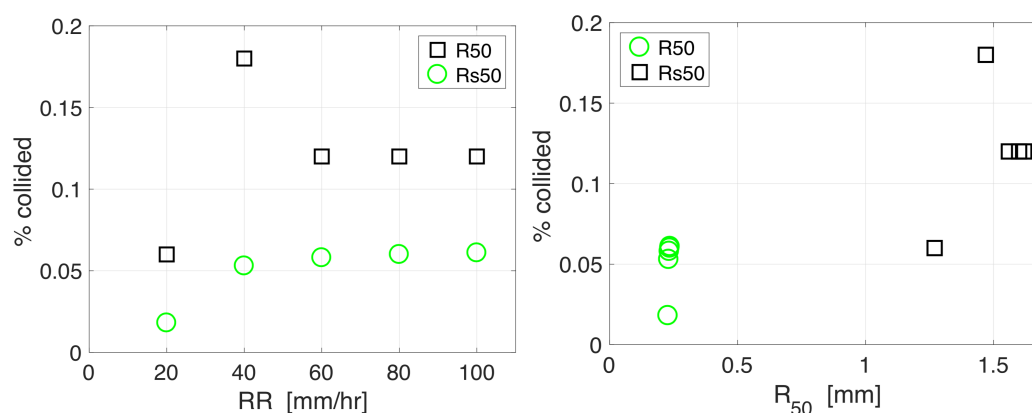


Figure 6. The collision ratio for different rain intensities and different droplet radii.

Additional simulations (not shown) suggest that when the wind velocity increases, the number of particles trapped by blade increases. However, when the particle radius becomes larger than 1.56 mm the ratio of the particles trapped by the blade does not change.

5. Summary and Discussion

Blade leading edge erosion influences turbine performance and energy capture. However, little is understood of the mechanisms how different hydrometeors influence the erosion process and specific to this research how best to simulate the collision efficiency and ultimately kinetic energy transfer to the blade leading edge. Since precipitation cannot be avoided where the turbine blades are installed, and precipitation varies extensively by location, amount and type [27-29], it is therefore of great scientific and practical merit to investigate the erosive potential in different precipitation regimes and the implications for blade leading edge erosion [30]. This work builds a set of numerical frameworks to quantify the roles of wind conditions and rain characteristics on the blade leading edge impaction probability. First, a 3D wind turbine aerodynamical numerical simulation system has been built. The simulation is based on ANSYS Fluent. The geometries used in this work are based on three different airfoil shapes in different locations, so that the lift forces generated on the blade are consistent with the blade rotating direction. The wind turbine numerically simulated comprises three blades, which are identical to each other. The numerical simulation system can be modified with different blade shape, blade length and other configurations, inlet wind velocity, and fluid temperature and density. The particles (hydrometeors) are currently assumed to be uniformly distributed by size and in the domain but could be modified with different user-defined functions to investigate different particle distributions.

This work acts as a necessary first step towards the challenge of understanding the intricate connection between hydrometeors, blade aerodynamics, and blade leading edge erosion, therefore it is by no means conclusive [28]. Additional investigation is needed to examine the processes involved.

First, a better rain model is required. Particles are currently considered to be uniformly distributed in the simulation domain, which requires a more observation-verified model. The rain droplets currently are assumed as spheres with constant radius. However, in natural rainfall, the rain droplets are of different sizes, hence, a better droplet function is also needed. Moreover, the rain droplets are represented as solids in the current work, which cannot change their form or break into smaller droplets. The single wind condition and the five rain intensity conditions may not be enough for us to derive critical values in terms of wind speed and particle size. Similarly, rain intensity varies from 20mmh^{-1} to 100mmh^{-1} here, which may not be representative of all the rain scenarios across all wind farms. In summary, more simulations with high resolution and more complex boundary conditions are also required.

Acknowledgments

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