

A Comparative Unsteady Aerodynamic Analysis of NACA 4412, 23012, and 63415 Airfoils: Effects of Rotational Speed and Reynolds Number

Tahar Benmessaoud^{1,*}, Ahmed Taibaoui²

¹Renewable Energy Systems Applications Laboratory (LASER), Faculty of Science and Technology, Ziane Achour University, Djelfa 17000, Algeria.

²Laboratory of Development in Mechanics and Materials (LDMM) - University of Djelfa, 17000, Algeria.

Emails: t.benmessaoud@univ-djelfa.dz; ahmed.taibaoui@univ-djelfa.dz.

* Corresponding Author Email: t.benmessaoud@univ-djelfa.dz;

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ABSTRACT

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A wind turbine's blade section is essential for capturing wind energy and producing clean, renewable energy. Every turbine blade is meticulously crafted with certain aerodynamic concepts in mind, with a primary emphasis on lift and drag forces. Optimizing energy capture and guaranteeing the overall efficiency of wind power systems require an understanding of the complexities of aerodynamics in this context. Using numerical simulations carried out with Ansys Fluent software, the current study examines the aerodynamics of three airfoils—NACA-4412, NACA-23012, and NACA-63415—with an emphasis on airflow patterns and performance. The computational method comprehensively investigates the effects of rotational speeds (from 2 to 16 degrees per second) and a variety of Reynolds numbers (from $1.25e6$ to $2e6$) using two-dimensional unsteady simulations. The results show how operational parameters and airflow patterns interact dynamically. Variations in velocity magnitude were detected, affected by rotational speeds and Reynolds numbers. These fluctuations gave further insights into flow behavior around the airfoil, such as the discovery of flow separation zones represented by velocity vectors. Analysis of lift coefficient values showed little variance concerning changes in rotational speed, indicating that 8 degrees per second is a suitable rotational speed for the cases under study. The values of the drag coefficient increased over time, with the NACA-63415 airfoil showing the highest values. Conversely, lift coefficient values showed a rising fluctuation that peaked at a certain value before trending downward. Notably, when compared to the other airfoils under study, the NACA 4412 airfoil showed better aerodynamic coefficients.

Keywords: Performance and airflow patterns, airfoil drag and lift coefficients, Two-dimensional unsteady simulations.

INTRODUCTION

The blade section of a wind turbine is essential for converting wind into clean, renewable energy. Each blade is meticulously designed based on aerodynamic principles, with a focus on lift and drag forces. Grasping the details of aerodynamics in this setting is vital for maximizing energy capture and ensuring the efficiency of wind power systems. (Leifsson & Koziel, 2015; Sharma, Gupta, Pandey, Sharma, & Mishra, 2021). In the literature, Numerous studies by (Almohammadi, 2022; Bayram, 2022; Erkan, Özkan, Karakoç, Garrett, & Thomas, 2020; Görgülü, Özgür, & Köse, 2021; Göv & Dođru, 2020; Koca, Genç, Açikel, Çağdaş, & Bodur, 2018; Oukassou, El Mouhsine, El Hajjaji, & Kharbouch, 2019; Tefera, Bright, & Adali, 2022; Yilmaz, Köten, Çetinkaya, & Coşar, 2018) have scrutinized the aerodynamic behaviors of NACA airfoils. These analyses encompass a variety of blade section forms, including NACA0012, NACA4412, NACA2412, NACA0009, NACA4415, NACA0015, and NACA63415. Employing a range of methodologies, from experimental to numerical approaches. The outcomes of these studies aim to identify optimal points encompassing blade section form, lift (CL) and drag (CD) coefficients, Pressure coefficient, Reynolds number from low to high, and angle of attack. The studies by (Nirooei, 2018; Ockfen & Matveev, 2009; Qu, Huang, Liu, Hu,

& Agarwal, 2017; Qu, Jia, Wang, Agarwal, & Liu, 2014; Qu, Jia, Wang, Liu, & Agarwal, 2014; Qu, Wang, Liu, & Agarwal, 2015; Sutardi & Fuad, 2023) collectively investigate the aerodynamic behavior of airfoils, particularly the NACA4412, under various conditions such as dynamic ground effect, extreme ground effect. Utilizing numerical simulations, experimental methods, and computational modeling techniques, these works elucidate intricate flow characteristics, pressure distributions, lift and drag forces, and their dependencies on factors like angle of attack, Reynolds number, and ground clearance. In order to that the wavy ground effects on the aerodynamic characteristics and flow field of NACA airfoils are examined in works of (Hu & Ma, 2020; Lee & Tremblay-Dionne, 2018; Liu, Ma, Yang, Guo, & Hu, 2021; Zhi et al., 2019). The present study provides a comparative analysis of the aerodynamics of three airfoils named NACA-4412, NACA-23012, and NACA-63415 with a specific focus on aerodynamic performance and airflow patterns, through two-dimensional unsteady simulations using Ansys Fluent software, the computational approach thoroughly explores the impact of rotational speeds (ranging from 2 to 16 degrees per second) and a range of Reynolds numbers from 1.25e6 to 2e6.

NUMERICAL METHODOLOGY

The numerical methodology employed in this study consists of four main steps. Firstly, the domain is created using the Design Modeler tool. in the second step, a computational mesh is generated. The third step involves configuring the solver using ANSYS Fluent. Finally, the results are subjected to post-processing.

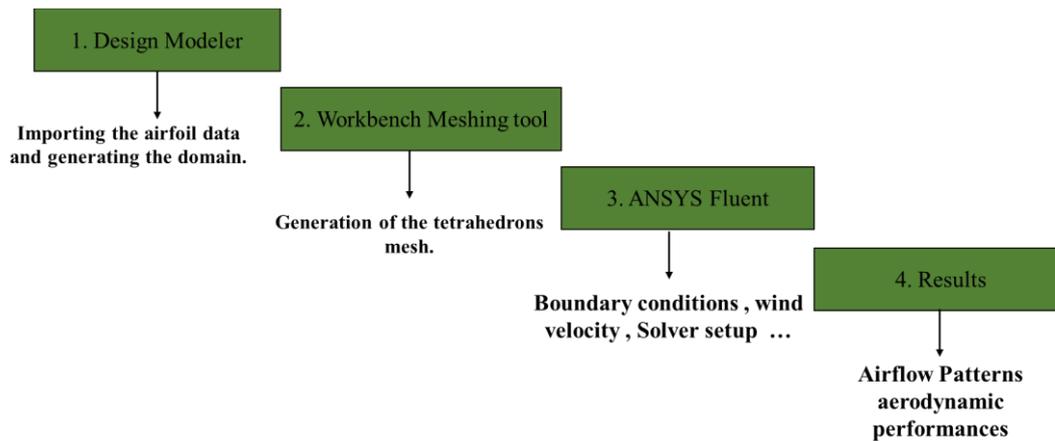


Figure 1: Numerical methodology steps.

GOVERNING EQUATIONS

The flow is governed by the unsteady-state Reynolds-Averaged Navier-Stokes (RANS) equations, describing momentum conservation, together with requirement for mass conservation (Alfonsi, 2009), the two relevant expressions are given by, respectively,

Continuity:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

Momentum:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j} (-\bar{u}'_i u'_j) \tag{2}$$

In Equation (2), \bar{p} represents mean pressure, ν stands for the fluid kinematic viscosity, and $-\bar{u}'_i u'_j$ denotes the Reynolds stresses. To accurately address turbulence effects, Reynolds stresses are modelled in order to achieve

closure of Equation (2). The method of modelling employed utilises the Boussinesq hypothesis to relate the Reynolds stresses to the mean velocity gradients within the flow. In order to that the study employs the K-Omega SST turbulence model (Nichols, 2010).

COMPUTATIONAL DOMAIN AND CALCULATION MESH

The constructed domain is partitioned into an inner circular shape (with a diameter five times that of the chord length) for accommodating variations in the angle of attack. Additionally, there is an outer domain featuring inlet and outlet boundaries. Within this entire domain, a structured mesh is generated, as depicted in Figure 2.

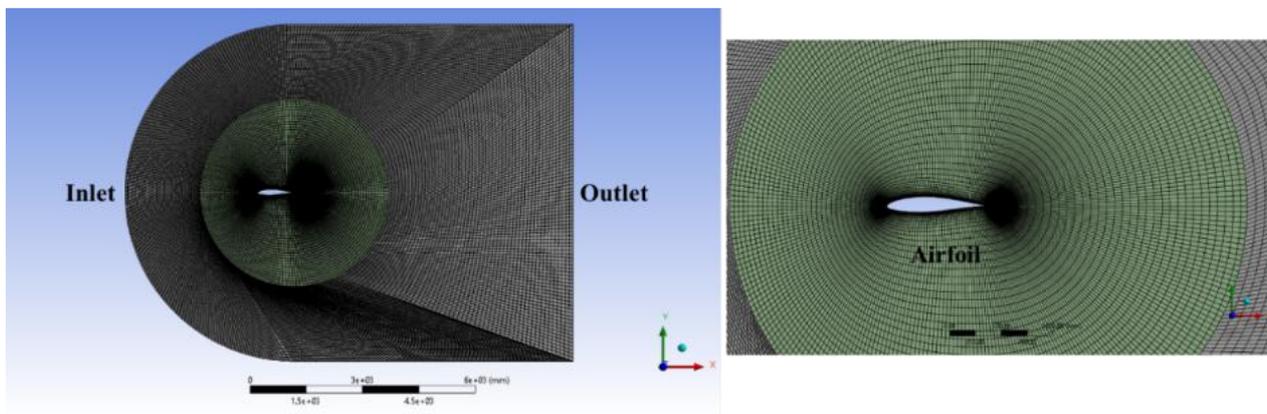


Figure 2: Computational domain.

RESULTS AND DISCUSSION

A mesh sensitivity analysis was conducted to verify the suitability of the mesh for the simulations. The results, depicted in Table 1, indicated that the optimal number of mesh cells for the current study was 31030 cells. This value was utilized to generate the final mesh for the simulations. An analysis of time step variation including three values (Dt=0.002, Dt=0.02, and Dt=0.2s) revealed the use of Dt=0.02s for the current simulations (see Table 2). Additionally, the Figure presents a comparison between the numerical findings of this study and experimental data (Coles & Wadcock, 1979) and numerical results (Tagawa, Morency, & Beaugendre, 2018) to validate the numerical approach used in the present study the comparison revealed an acceptable agreement between the datasets.

Table 1 : Mech cells variation analysis

Time (s)	51569 Cells	31030 Cells	17648 Cells	Err %	Err %2
1.000	0.582	0.579	0.578	0.43%	0.13%
3.000	0.960	0.957	0.957	0.32%	-0.06%
6.000	1.447	1.447	1.440	0.02%	0.46%
9.000	1.674	1.690	1.652	-0.92%	2.25%
11.500	1.444	1.479	1.414	-2.42%	4.38%

Table 2: Time step variation analysis

Time (s)	DT = 0.002	DT = 0.02	DT = 0.2	Err %	Err %2
1.000	0.582	0.579	0.582	0.499%	-0.567%
3.000	0.960	0.957	0.958	0.384%	-0.138%
6.000	1.449	1.447	1.439	0.140%	0.562%
9.000	1.681	1.690	1.631	-0.505%	3.492%
11.000	1.528	1.479	1.460	3.208%	1.300%

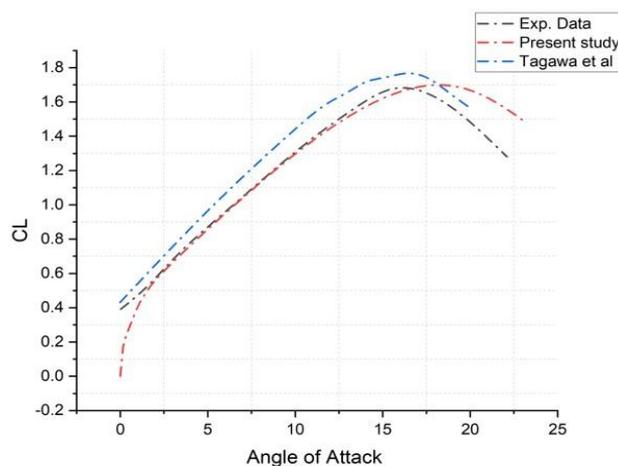


Figure 3: Numerical approach Validation.

Figure 4 illustrate graphs of the lift coefficient as a function of the angle of attack within the specified range of [0 to 23 degrees] at a Reynolds number of $2e6$. The analysis focuses on the NACA-4412 airfoil, incorporating a range of rotational speeds (from 2 to 16 degrees per second). From these figures, it is evident that there is a small variation in lift coefficient values concerning the change in rotational speed, allowing for the selection of 8 degrees per second as the accepted rotational speed for the remaining studied cases.

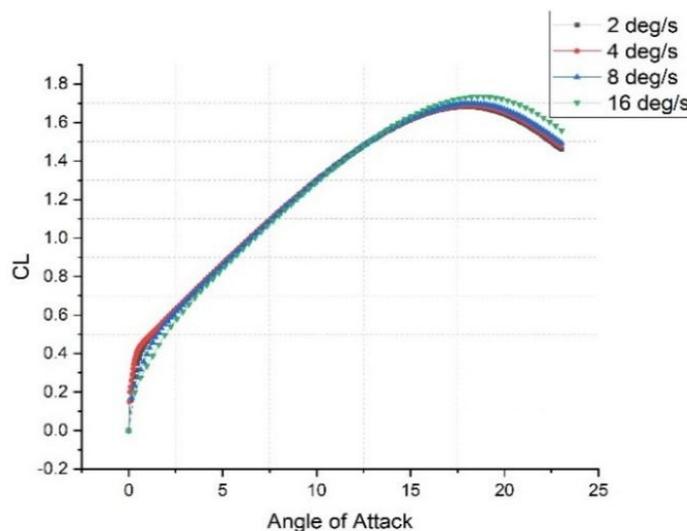


Figure 4: Lift coefficient in function of angle of attack.

Figures 5 and 6 illustrate graphs of drag and lift coefficients as functions of time for the specified range of [0 to 3s] and several Reynolds numbers (1.25e6, 1.5e6, 1.75e6, and 2e6). within the utilized rotational speed of 8 degrees per second, the analysis encompasses a range of angles of attack (from 0 to 23 degrees). in order to that the analysis considered three airfoils named NACA-4412, NACA-23012, and NACA-63415, from these figures, it is clear that the lift coefficient values exhibit an increasing variation to a maximum value after that a decreasing trend can be noticeable, the maximum values are 1.67 at 2.28 (s), 1.45 at 2.22 (s) and 1.33 at 1.9 (s), which correspond to 18.24, 17.76 and 15.2 degrees for the airfoil NACA-4412, NACA-23012, and NACA-63415, respectively. In order to that the drag coefficient values exhibit an increasing variation over time with high values in the case of NACA-63415.

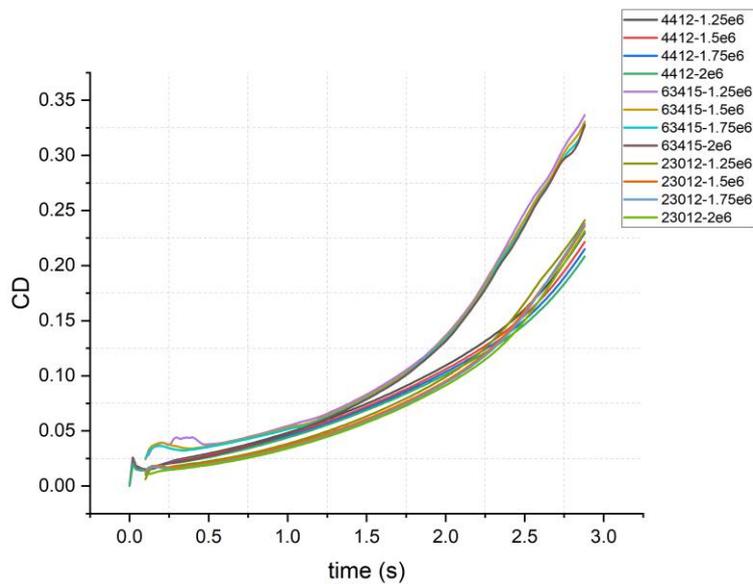


Figure 5: Drag coefficient in function of time.

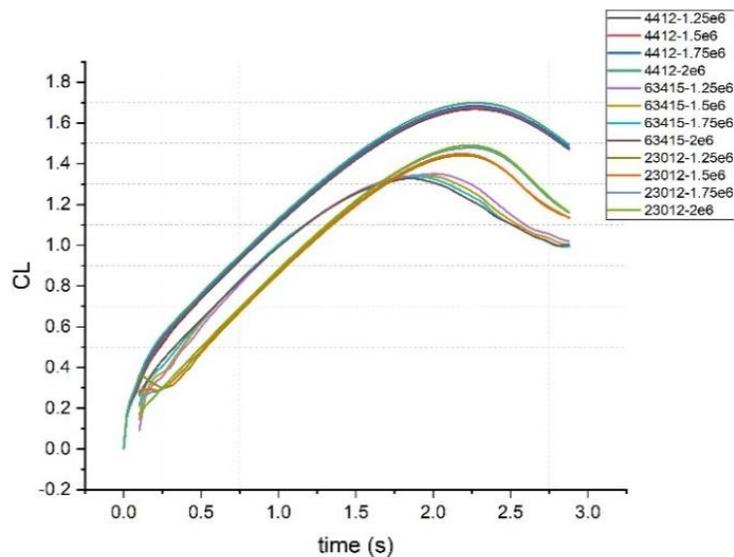


Figure 6: Lift coefficient in function of time.

Figures 7 and 8 present visualizations of velocity magnitude and velocity vectors, examining the aerodynamic characteristics of three airfoils named NACA-4412, NACA-23012, and NACA-63415. Within these figures, twelve images are displayed, illustrating different angles of attack (17.28 and 23.04 degrees) at a Reynolds number of 2E6. A noteworthy observation is the presence of a region with minimum values near the trailing edge of the airfoils. This region becomes more pronounced with an increase in the angle of attack, aligning consistently with the flow separation region identified in the velocity vectors.

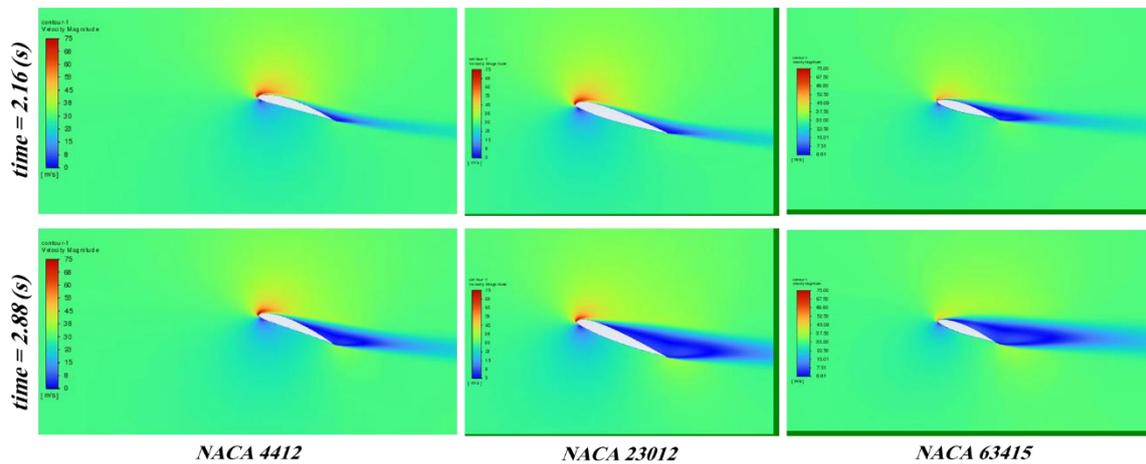


Figure 7: Velocity Magnitude.

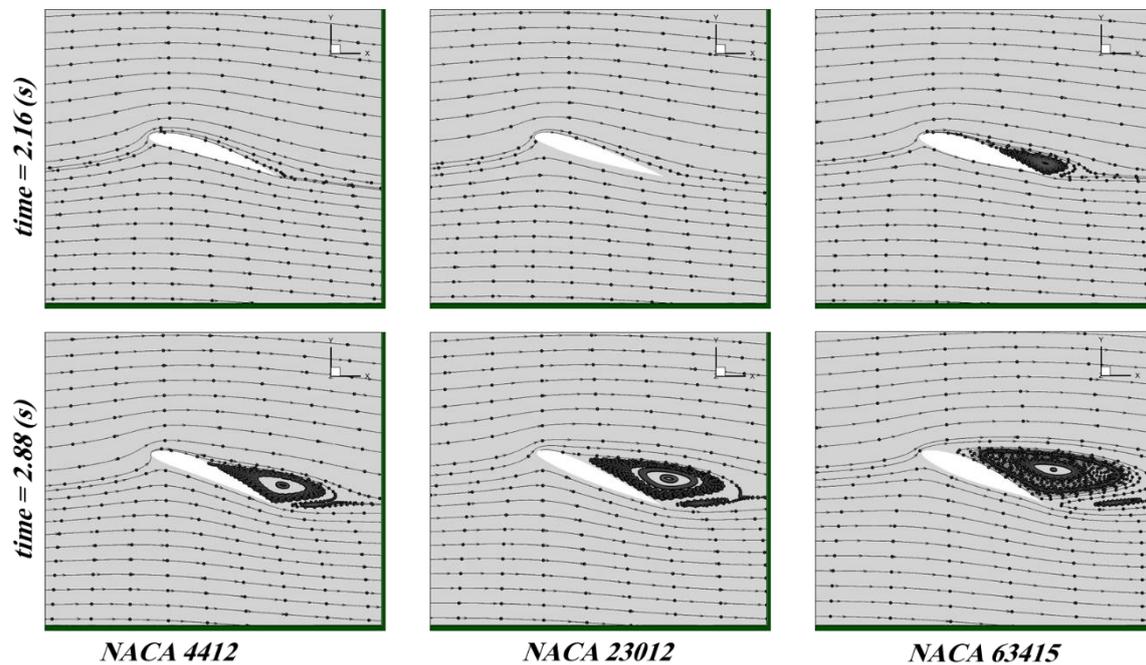


Figure 8: Velocity Vectors.

CONCLUSIONS

In conclusion, this paper delved into the aerodynamics of three airfoils—NACA-4412, NACA-23012, and NACA-63415—employing numerical simulations through Ansys Fluent software. The primary focus of the study was on evaluating performance and airflow patterns. Employing two-dimensional unsteady simulations, the computational approach thoroughly explored the effects of rotational speeds (ranging from 2 to 16 degrees per second) and a range

of Reynolds numbers from $1.25e6$ to $2e6$. The findings highlighted the dynamic interplay between airflow patterns and operational factors.

Key observations from the study include:

- Changes in velocity magnitude were observed, which were impacted by Reynolds numbers and rotating speeds. As demonstrated by the velocity vectors, these fluctuations offered further information about the flow behaviour close to the aerofoil, including the identification of flow separation zones.
- The analysis of lift coefficient values demonstrated a limited variance concerning changes in rotational speed, indicating that 8 degrees per second is an adequate rotational speed for the studied cases.
- An examination of airfoil aerodynamic coefficient trends revealed substantial findings. Drag coefficient values increased over time, with greater values found for the NACA-63415 airfoil. Lift coefficient values, on the other hand, showed increasing variety, peaking at a value and then declining. Notably, the NACA 4412 airfoil has higher aerodynamic coefficients than the other airfoils tested.

Moreover, the study's findings have practical implications for the design and optimization of wind turbine blades. The superior performance of the NACA 4412 airfoil suggests its potential for enhanced energy capture efficiency in wind turbine applications. By understanding the detailed aerodynamic behavior of different airfoils, designers can make informed decisions about blade shape and configuration, leading to more efficient and reliable wind turbines. The comprehensive analysis provided by this paper contributes to the field of wind energy, supporting the development of more effective strategies for harnessing wind power and advancing the goal of sustainable energy production. However, the study has limitations due to its two-dimensional settings, which do not fully capture the complexity of three-dimensional flow effects in wind turbine blades. Additionally, the study focused on a specific range of Reynolds numbers and rotational speeds, which may not cover all operational conditions experienced by wind turbines. This could affect the generalizability of the findings to different wind conditions. Future research should address these limitations through three-dimensional simulations, and a broader range of operational conditions.

CONFLICTOFINTEREST

The authors declare no conflict of interest.

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