

# Recent Advances on Machine Learning for Computational Fluid Dynamics: A Survey

Haoxin Wang, Yadi Cao, Zijie Huang, Yuxuan Liu, Peiyan Hu, Xiao Luo, Zezheng Song, Wanjia Zhao, Jilin Liu, Jinan Sun<sup>†</sup>, Shikun Zhang, Long Wei, Yue Wang, Tailin Wu, Zhi-Ming Ma, Yizhou Sun

**Abstract**—This paper explores the recent advancements in enhancing Computational Fluid Dynamics (CFD) tasks through Machine Learning (ML) techniques. We begin by introducing fundamental concepts, traditional methods, and benchmark datasets, then examine the various roles ML plays in improving CFD. The literature systematically reviews papers in recent five years and introduces a novel classification for forward modeling: Data-driven Surrogates, Physics-Informed Surrogates, and ML-assisted Numerical Solutions. Furthermore, we also review the latest ML methods in inverse design and control, offering a novel classification and providing an in-depth discussion. Then we highlight real-world applications of ML for CFD in critical scientific and engineering disciplines, including aerodynamics, combustion, atmosphere & ocean science, biology fluid, plasma, symbolic regression, and reduced order modeling. Besides, we identify key challenges and advocate for future research directions to address these challenges, such as multi-scale representation, physical knowledge encoding, scientific foundation model and automatic scientific discovery. This review serves as a guide for the rapidly expanding ML for CFD community, aiming to inspire insights for future advancements. We draw the conclusion that ML is poised to significantly transform CFD research by enhancing simulation accuracy, reducing computational time, and enabling more complex analyses of fluid dynamics. The paper resources can be viewed at <https://github.com/WildDroamer/Awesome-AI4CFD>.

**Index Terms**—Machine Learning, Computational Fluid Dynamics, AI for PDE, Physics Simulation, Inverse Problem.

## 1 INTRODUCTION

**F**LUID dynamics is a fundamental discipline that studies the motion and behavior of fluid flow. It serves as a foundation across a wide range of scientific and engineering fields, including aerodynamics [1], [2], [3], chemical engineering [4], [5], [6], biology [7], [8], [9], and environmental science [10], [11], [12], [13], [14], [15]. CFD employs mathematical models to simulate fluid dynamics through partial differential equations (PDEs) [16]. The primary goal of CFD is to obtain simulated results under various working conditions, thereby reducing the need for costly real-world experiments and accelerating engineering design and control processes.

Despite decades of advancement in research and engineering practice, CFD techniques continue to face significant challenges. These include high computational costs due to demanding restrictions on spatial or temporal resolutions, difficulties in capturing subscale dynamics such as in turbulence [17], and stability issues with numerical algorithms [16], among others. On the other hand, ML, famous for its ability to learn patterns and dynamics from observed data, has recently emerged as a trend that can reshape or enhance any general scientific subject [18]. The integration

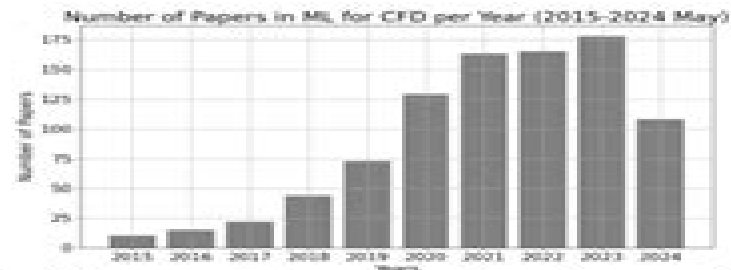


Fig. 1: The approximate annual number of papers on ML for CFD presented at top-tier ML publication and leading journals in fluid dynamics appeared in Table 1 and 2

of ML techniques with the extensive fluid dynamics data accumulated over recent decades offers a transformative approach to augment CFD practices (see Fig. 1). As the field of ML continues to expand rapidly, it becomes increasingly challenging for researchers to stay updated. In response, this review aims to shed light on the multifaceted roles ML plays in enhancing CFD.

Actually, there have already been some surveys on the application of ML methods in the CFD field. However, most of these surveys have the following two limitations: 1) **Only earlier attempts**. For instance, Wang *et al.* [19] and Huang *et al.* [20] both provide a detailed discussion on incorporating physics-based modeling into ML, emphasizing dynamic systems and hybrid approaches. Similarly, Vinuesa *et al.* [21] explores promising ML directions from the perspective of CFD domain, such as direct numerical simulations, a

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 • P. Hu and Z. Ma are from Academy of Mathematics and Systems Science, Chinese Academy of Sciences.  
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 • L. Wei and T. Wu work at Westlake University.  
 • Y. Wang works at Microsoft AHSIcenter.  
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# Recent Advances In Computational Fluid Dynamics

**Esteban Ferrer, Adeline Montlaur**



## **Recent Advances In Computational Fluid Dynamics:**

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From the preface Fluid dynamics is an excellent example of how recent advances in computational tools and techniques permit the rapid advance of basic and applied science The development of computational fluid dynamics CFD has opened new areas of research and has significantly supplemented information available from experimental measurements Scientific computing is directly responsible for such recent developments as the secondary instability theory of transition to turbulence dynamical systems analyses of routes to chaos ideas on the geometry of turbulence direct simulations of turbulence three dimensional full aircraft flow analyses and so on We believe that CFD has already achieved a status in the tool kit of fluid mechanics equal to that of the classical scientific techniques of mathematical analysis and laboratory experiment

**Recent Advances in Computational Mechanics and Simulations** Sandip Kumar Saha, Mousumi Mukherjee, 2020-11-13 This volume presents selected papers from the 7th International Congress on Computational Mechanics and Simulation held at IIT Mandi India The papers discuss the development of mathematical models representing physical phenomena and applying modern computing methods and simulations to analyse them The studies cover recent advances in the fields of nano mechanics and biomechanics simulations of multiscale and multiphysics problems developments in solid mechanics and finite element method advancements in computational fluid dynamics and transport phenomena and applications of computational mechanics and techniques in emerging areas The volume will be of interest to researchers and academics from civil engineering mechanical engineering aerospace engineering materials engineering science physics mathematics and other disciplines      **Recent Advances in Fluid Dynamics** Jyotirmay Banerjee, Rupesh D. Shah, Ramesh K. Agarwal, Sushanta Mitra, 2022-09-24 This book presents select proceedings of the International Conference on Advances in Fluid Flow and Thermal Sciences ICAFFTS 2021 and summarizes the modern research practices in fluid dynamics and fluid power The content of the book involves advanced topics on turbulence droplet deposition oscillating flows wave breaking spray structure and its atomization and flow patterns in mini and micro channels Technological concerns relevant to erosion of steam turbine blade due to droplets influence of baffle cut and baffle pitch on flow regime bubble formation and propagation in pool boiling design optimization of flow regulating valves are included in the book In addition recent trends in small scale hydropower plant and flow stability issues in nanofluids solar water heating systems and closed loop pulsating heat pipes are discussed Special topics on airflow pattern in railway coach and vortex tube are also included This book will be a reliable reference for academicians researchers and professionals working in the areas of fluid dynamics and fluid power      **Recent Advances In Computational Science And Engineering - Proceedings Of The**

**International Conference On Scientific And Engineering Computation (Ic-sec) 2002** Justin Kwok, Heow-pueh

Lee, Kurichi Kumar, 2002-12-02 IC SEC 2002 serves as a forum for engineers and scientists who are involved in the use of high performance computers advanced numerical strategies computational methods and simulation in various scientific and engineering disciplines The conference creates a platform for presenting and discussing the latest trends and findings about the state of the art in their particular fields of interest IC SEC also provides a forum for the interdisciplinary blending of computational efforts in various diversified areas of science such as biology chemistry physics and materials science as well as all branches of engineering The proceedings cover a broad range of topics and an application area which involves modelling and simulation work using high performance computers

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Michael Schäfer, Marek Behr, Miriam Mehl, Barbara Wohlmuth, 2018-08-21 This book comprises the proceedings of the 4th International Conference on Computational Engineering ICCE 2017 held in Darmstadt Germany on September 28 29 2017 The conference is intended to provide an interdisciplinary meeting place for researchers and practitioners working on computational methods in all disciplines of engineering applied mathematics and computer science The aims of the conference are to discuss the state of the art in this challenging field exchange experiences develop promising perspectives for future research and initiate further cooperation Computational Engineering is a modern and multidisciplinary science for computer based modeling simulation analysis and optimization of complex engineering applications and natural phenomena The book contains an overview of selected approaches from numerics and optimization of Partial Differential Equations as well as uncertainty quantification techniques typically in multiphysics environments Where possible application cases from engineering are integrated The book will be of interest to researchers and practitioners of Computational Engineering Applied Mathematics Engineering Sciences and Computer Science

Some Recent Advances in Computational Aerodynamics for Helicopter Applications W. J. McCroskey, 1985

*Special Issue: Recent Advances in Simulations of*

*CFD-based* Pengfei Liu, Chemical Society of Canada, 2006

**Parallel Computational Fluid Dynamics** Rupak Biswas, 2010

**Recent Advances in CFD for Wind and Tidal Offshore Turbines** Esteban Ferrer, Adeline Montlaur, 2019-02-06 The book presents novel Computational Fluid Dynamics CFD techniques to compute offshore wind and tidal applications The papers in this volume are based on a mini symposium held at ECCOMAS 2018 Computational fluid dynamics CFD techniques are regarded as the main design tool to explore the new engineering challenges presented by offshore wind and tidal turbines for energy generation The difficulty and costs of undertaking experimental tests in offshore environments have increased the interest in CFD which is used to design appropriate turbines and blades understand fluid flow physical phenomena associated with offshore environments predict power production or characterise offshore environments amongst other topics

Recent Advances in Energy Technologies N. Lakshmi Narasimhan, Mahmoud Bourouis, Vasudevan

Raghavan, 2022-09-29 This book presents the select proceedings of the first International Conference on Energy and Materials Technologies ICEMT 2021 organized by the Department of Mechanical Engineering Sri Sivasubramaniya Nadar

College of Engineering Kalavakkam India It covers the recent technologies in two broad thematic areas energy and materials Various topics covered in this book include hybrid energy advanced energy systems energy management energy policy geothermal nuclear energy bio energy waste to energy power plants and automotives The book will be useful for students researchers and professionals in the area of mechanical engineering especially various domains of energy *Recent Advances in Mechanical Engineering, Volume 1* Gujjala Raghavendra, B. B. V. L. Deepak, Manoj Gupta, 2024-04-01 This book presents select proceedings of International Conference on Mechanical Engineering Researches and Evolutionary Challenges ICMech REC 23 It covers the latest research in the areas of mechanical engineering and materials applications Various topics covered in this book are materials composite nano advanced design methodologies Industry 4.0 smart manufacturing thermodynamics mechatronics robotics soft computing and automation The contents of this book are useful to the researchers and professionals working in the different areas of mechanical engineering Recent Advances in Mechatronics Tomas Brezina, Ryszard Jablonski, 2009-11-29 Mechatronics is a synergic discipline integrating precise mechanics electrotechnics electronics and IT technologies The main goal of mechatronical approach to design of complex products is to achieve new quality of their utility value at reasonable price Successful accomplishment of this task would not be possible without application of advanced software and hardware tools for simulation of design technologies and production control and also for simulation of behavior of these products in order to provide the highest possible level of spatial and functional integration of the final product This book brings a review of the current state of the art in mechatronics as presented at the 8th International Conference Mechatronics 2009 organized by the Brno Technical University Faculty of Mechanical Engineering Czech Republic The specific topics of the conference are Modelling and Simulation Metrology Diagnostics Sensorics Photonics Control Robotics MEMS Design Mechatronic Products Production Machines and Biomechanics The selected contributions provide an insight into the current development of these scientific disciplines present the new results of research and development and indicate the trends of development in the interdisciplinary field of mechatronic systems Therefore the book provides the latest and helpful information both for the R D specialists and for the designers working in mechatronics and related fields Recent Advances in Energy Transitions Towards Sustainable Development Avijit Ghosh, Vilas Sapkal, U. Kamachi Mudali, 2025-08-08 This book presents the select proceedings of the 76th Indian Chemical Engineering Congress CHEMCON 2023 which was focused on energy transitions towards sustainable development It includes the latest developments in the energy science and engineering towards sustainable development It also discusses the role of machine learning IoT in chemical engineering Various topics covered include chemical engineering process engineering biofuel and biosafety advanced techniques for waste to wealth generation bioinformatics for energy transition green and renewable membranes and carbon capture sequestration and utilization electrochemical energy biodiesel and bioplastics toward low carbon footprint and sustainable food packaging The book will be a valuable reference for researchers

and professionals interested in sustainable energy and allied fields      Computational Fluid Dynamics Guozhao Ji,Jingliang Dong,2023-12-20 Computational fluid dynamics CFD is a powerful tool that enables engineers and scientists to simulate fluid flows in a variety of applications including thermal engineering biomedical engineering and environmental modeling This book provides a comprehensive introduction to CFD encompassing fundamental theory mathematical and numerical techniques and practical applications The book begins by systematically introducing the basic concepts and terminology of CFD such as the continuity equation Navier Stokes equations energy equation source sink terms and types of grids The mathematical and numerical methods utilized to solve the CFD governing equations including the finite difference method and the finite volume method are then described in a beginner friendly manner accompanied by vivid and straightforward graphical illustrations In addition to covering the foundation of CFD theory the book presents several practical applications of CFD in diverse fields such as biomedical modeling renewable energy and thermal engineering To extract useful information the simulated CFD results need to be analyzed and visualized Therefore the book demonstrates common post processing and visualization techniques such as contour plots streamlines vectors and charts Overall this book provides a comprehensive introduction to CFD encompassing the essential theory methods and applications making it an ideal choice as a textbook for graduate and post graduate students or a reference for researchers and engineers working on CFD simulations      *IUTAM Symposium on Recent Advances in Moving Boundary Problems in Mechanics* Stefanie Gutschmidt,James N. Hewett,Mathieu Sellier,2019-03-28 Many problems in mechanics involve deformable domains with moving boundaries including fluid structure interaction multiphase flows flows over soft tissues and textiles or flows involving accretion erosion to name but a few The presence of a moving boundary presents considerable challenges when it comes to modelling and understanding the underlying system dynamics This proceedings volume collects contributions made at the IUTAM Symposium on Recent Advances in Moving Boundary Problems in Mechanics held in Christchurch New Zealand in February 2018      Recent Advances in Materials, Mechanics and Structures Suman Saha,A. S. Sajith,Dipti Ranjan Sahoo,Pradip Sarkar,2022-10-04 The book presents the select proceedings of the second International Conference on Materials Mechanics and Structures ICMMS 2022 The book highlights the latest developments innovations and applications in the diverse range of areas of civil engineering It covers the findings of recent research works across the globe on various topics such as civil engineering materials concrete and masonry structures composite structures structural mechanics fluid structure interaction repair rehabilitation and retrofitting of the structures new technologies in structural design and construction bridge engineering structural dynamics earthquake engineering etc This book will be useful for beginners researchers and professionals working in the different areas of civil engineering      *Recent Advancements in Product Design and Manufacturing Systems* B B V L Deepak,M.V.A. Raju Bahubalendruni,D.R.K. Parhi,B. B. Biswal,2024-11-16 This book presents select proceedings of the 5th Innovative Product Design and Intelligent Manufacturing System IPDIMS 2023

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