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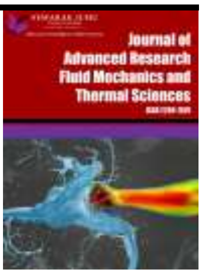

A Comprehensive Survey of Open-Source Tools for Computational Fluid Dynamics Analyses

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ABSTRACT

Computational Fluid Dynamics (CFD), blending disciplines like fluid mechanics and computer science, plays a pivotal role in various engineering and scientific endeavors. Despite its importance, the prohibitive costs and restricted access to commercial CFD tools pose significant barriers. This study addresses the need for accessible CFD solutions by conducting a comprehensive review of open-source CFD tools, highlighting their role in promoting open science. Through methodical analysis, the present study explores the capabilities, performance, and applicability of these tools in various contexts. The findings reveal that open-source CFD tools not only offer a cost-effective alternative to proprietary software but also foster collaboration and transparency in the scientific community. This study concludes that these tools are not only viable but essential for the advancement of CFD applications, encouraging wider adoption and development. This review serves as a bridge in the literature, enhancing understanding and accessibility of open-source tools in CFD, and supporting the paradigm shift towards open science.

1. Introduction

Computational Fluid Dynamics (CFD), an interdisciplinary field combining fluid mechanics, heat transfer, computational methods, and computer science, has revolutionized fluid flow and heat exchange analysis [1-4]. Its applications range from aerospace engineering to environmental modeling, establishing it as a cornerstone of modern scientific and engineering practices [5-11]. However, the high costs and proprietary nature of commercial CFD tools have limited their accessibility. This situation highlights the growing importance of open-source tools in CFD, which offer cost-effective solutions and embrace open science principles, fostering collaboration and transparency in research.

Despite their growing popularity, there is a significant gap in the literature regarding a comprehensive understanding of these tools. Many in the scientific community are not fully aware

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of the capabilities of open-source CFD tools. This study aims to fill this gap by providing a thorough review of these tools, examining their features, applications, and impact. This paper explores various open-source CFD tools and discusses their practical applications in areas like geometry modeling, mesh generation, simulation, and post-processing. The main goal is to guide the CFD community in leveraging these open-source resources, paving the way for a more open, collaborative scientific future. This study provides an exhaustive review of open-source tools in CFD underscoring their unique contributions and potential to reshape the field.

2. Open-source Tools

The rising popularity of open-source CFD tools shown in Figure 1 can be attributed largely to their cost-effectiveness and can be customized as per user requirements, offering a clear benefit over commercial options. These tools are especially beneficial for small companies and individual researchers with limited budgets, as they eliminate the need for expensive licensing fees.

Fig. 1. CAE open-source simulation solvers [12]

Moreover, their customizable nature allows users to tailor the tools to their specific needs, flexibility often restricted in commercial software. One of the key advantages of open-source tools is their transparency. Users can inspect, verify, and test the code for accuracy and reliability, an essential aspect in scientific fields like CFD as shown in Figure 2(a) and Figure 2(b) both of which shows the comparison of the results obtained from commercial Ansys Fluent and open source software called OpenFOAM. This transparency not only fosters a deeper understanding of algorithms and numerical methods among students and researchers but also stimulates innovation in fluid dynamics research. Additionally, the robust support community and continuous development associated with open-source tools enhance their reliability and offer assistance, simplifying both learning and problem-solving.

These tools are also versatile, capable of being used in diverse areas and easily integrated into various workflows. In essence, open-source tools are transforming CFD by making sophisticated, adaptable tools widely accessible, fostering a collaborative environment conducive to learning and innovation. This is well exemplified by the use of OpenFOAM in small-scale aerospace projects, which has shown significant cost savings and flexibility, demonstrating the practical advantages of these tools in real-world applications. To enhance the user-friendliness of open-source software, developers have integrated tools like OpenFOAM into more accessible GUI environments, complemented by additional software for pre- and post-processing, such as Visual-CFD, HELYX, and simFlow. While these wrappers offer the convenience of a unified interface, they introduce an extra layer between the user and the execution code. The main advantage of using wrappers is their ability to provide some benefits of comprehensive commercial platforms at a lower cost. However, they also have downsides, including not addressing some core limitations of open-source software, such as limited user support and specialized features. Additionally, these wrappers bring their own potential issues, including bugs and possibly inadequate support and development.

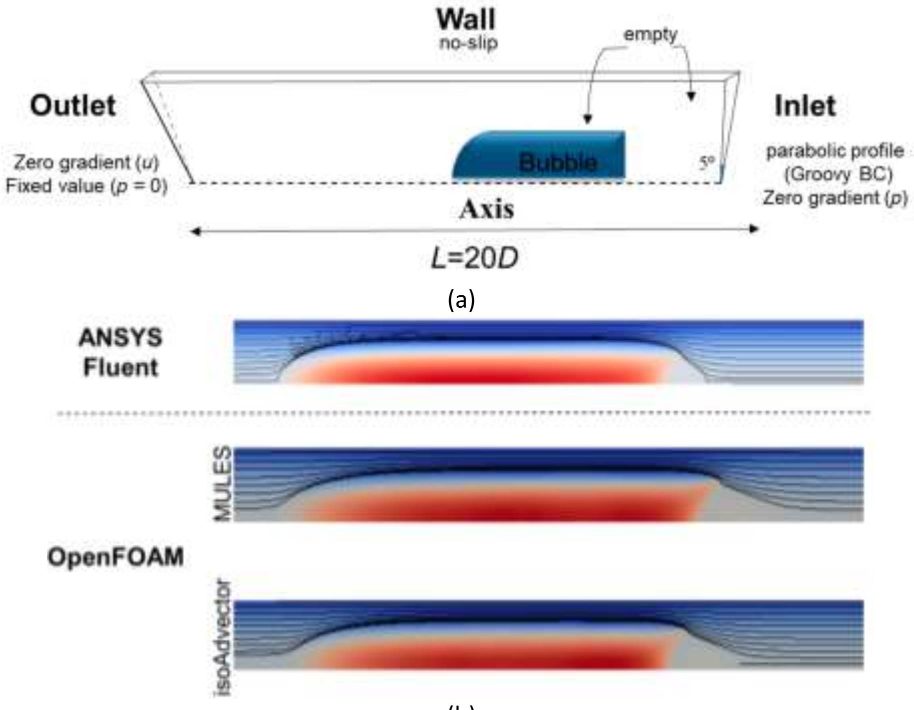


Fig. 2. (a) Domain and boundary conditions of bubble with OpenFOAM, (b) Comparison between ANSYS Fluent and OpenFOAM analysis with velocity streamlines at Re = 10 [13]

3. Comparison between Commercial and Open-source Tools

An open-source tool, is free and allows extensive customization, making it ideal for specialized research or unique simulation demands. Its flexibility is enhanced by the ability to modify and extend the code, especially useful for those proficient in programming skills. However, its less intuitive interface and steep learning curve, coupled with community-driven support, make it more challenging to master. Open-source tools are particularly accessible for individuals, small companies, or educational institutions with limited budgets. On the other hand, a commercial tool, is known for its user-friendly interface, making it easier for newcomers. It offers regular updates, dedicated customer support, and technical training as part of its licensing. Commercial tools seamlessly integrate with other tools for multi-physics simulations and provides advanced models and features right out of the box. However, its significant cost can be a barrier for smaller entities, and it offers less flexibility for customization than open-source. The license varies in cost from thousands to lakhs depending on usage, and there is a limitation on cell/nodes for student licenses. Open-source is more suited for users seeking deep customization, possessing programming skills, and engaged in unique or research-focused projects. Commercial tools cater more to commercial applications and users favoring an intuitive interface with less emphasis on customization. The choice between them hinges on the specific needs, budget, and expertise of the user or organization.

Computational Fluid Dynamics (CFD) is a specialized field in engineering and physics that involves the simulation of fluid flow and heat transfer using numerical methods. CFD software can be broadly classified into two categories: commercial and open-source. In this comparison in Table 1, various aspects of both types to help users make informed decisions based on their specific needs.

Table 1
Comparison between commercial and open-source entities based on various factors

Comparative Factor	Commercial	Open-Source
Cost	• Typically involves licensing fees, which can be substantial. • Additional costs for maintenance, updates, and support.	• Free to download and use, reducing financial barriers. • However, costs may still be incurred for training, support and hardware.
Code Accessibility and Transparency	• Closed-source, limiting the ability to modify or customize the code. • Users rely on the software provider for updates and bug fixes.	• Source code is accessible, allowing users to modify and customize. • Community-driven development often leads to frequent updates and bug fixes.
Community Support	• Typically comes with professional support services. • User forums and community support may be available but might not be as extensive.	• Relies on community support, which can be strong and active. • Extensive user forums and collaborative development.
Solver Capabilities	• Often provides a wide range of pre-built, validated solvers for various applications. • Proprietary solvers may be more user-friendly for non-experts.	• Variety of solvers available, and users can modify or develop their own. • May require more expertise to set up and use effectively.
User Interface and Ease of Use	• Generally comes with a polished, user-friendly graphical interface. • Aimed at a broader audience, including engineers with limited programming knowledge.	• User interfaces can vary in quality; some may be less intuitive. • Greater flexibility but may require more technical expertise.
Application Range	• Often covers a broad spectrum of applications with specialized modules. • Well-suited for industries with specific requirements and regulations.	• Flexibility to adapt to a wide range of applications but may require more user effort. • Well-suited for research, academic, and non-commercial purposes.
Integration with their Software	• May have better integration with other proprietary engineering software. • Plug-and-play solutions for specific industries.	• Open standards facilitate interoperability but may require more user effort. • Integration with other open-source tools may be straightforward.
Documentation and Training	• Generally comes with comprehensive documentation and user manuals. • Professional training programs may be available.	• Documentation quality can vary, but community-driven projects often have extensive guides. • Learning resources may include tutorials, online courses, and community forums.

The choice between commercial and open-source CFD software depends on various factors, including budget, application requirements, user expertise, and the level of customization needed. Commercial software may be preferable for industries with specific needs and a larger budget, while open-source options provide flexibility, accessibility, and community-driven support for research and educational purposes.

4. Foundations of Computational Fluid Dynamics

In a typical CFD analysis shown in Figure 3, defining the problem and the objectives of the study is the pivotal first step, requiring a thorough understanding of the physical processes involved, such as flow, heat transfer, and chemical reactions. This is followed by the selection of appropriate physical models, geometric modelling, mesh generation, and the meticulous assignment of boundary conditions. With the problem thus defined and contextualized, suitable numerical algorithms and solvers are employed to compute the flow and heat transfer. Following simulations, results are analysed, validated, and refined if necessary, culminating in comprehensive documentation and recommendations for design improvements or further analyses. Mastery of fluid mechanics, numerical methods, and specific software is crucial throughout the process to ensure the reliability and accuracy of the CFD analyses. Open-source tools provide a versatile and accessible framework for these foundational steps, offering extensive libraries and community-driven support for model selection, geometric modelling, and boundary condition assignment.

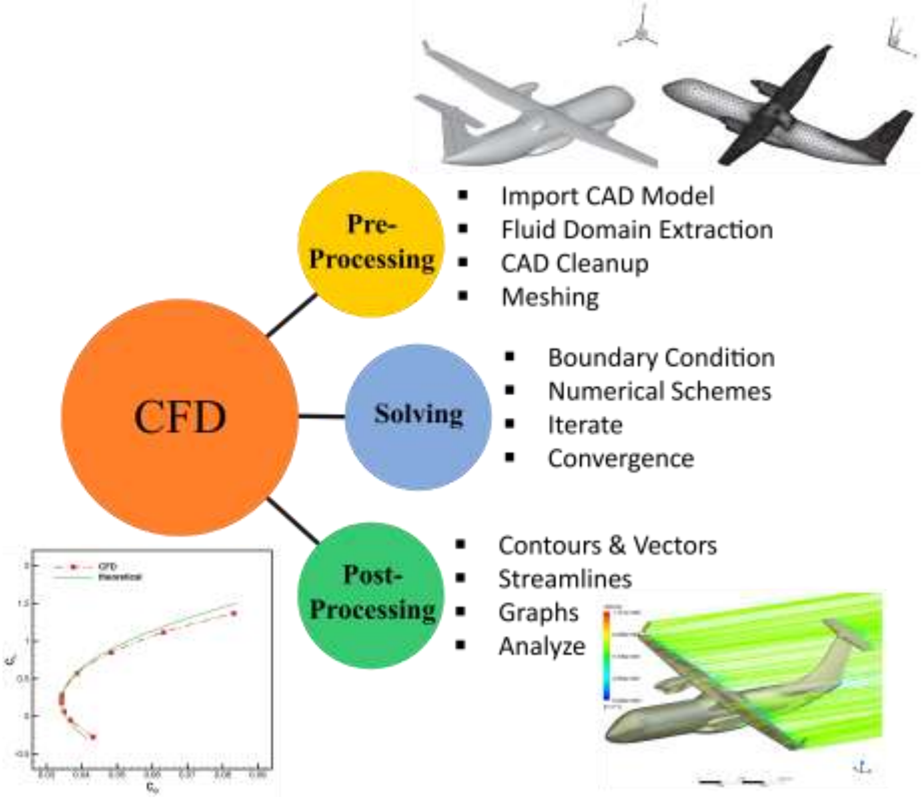


Fig. 3. Primary steps involved in CFD analysis [14,15]

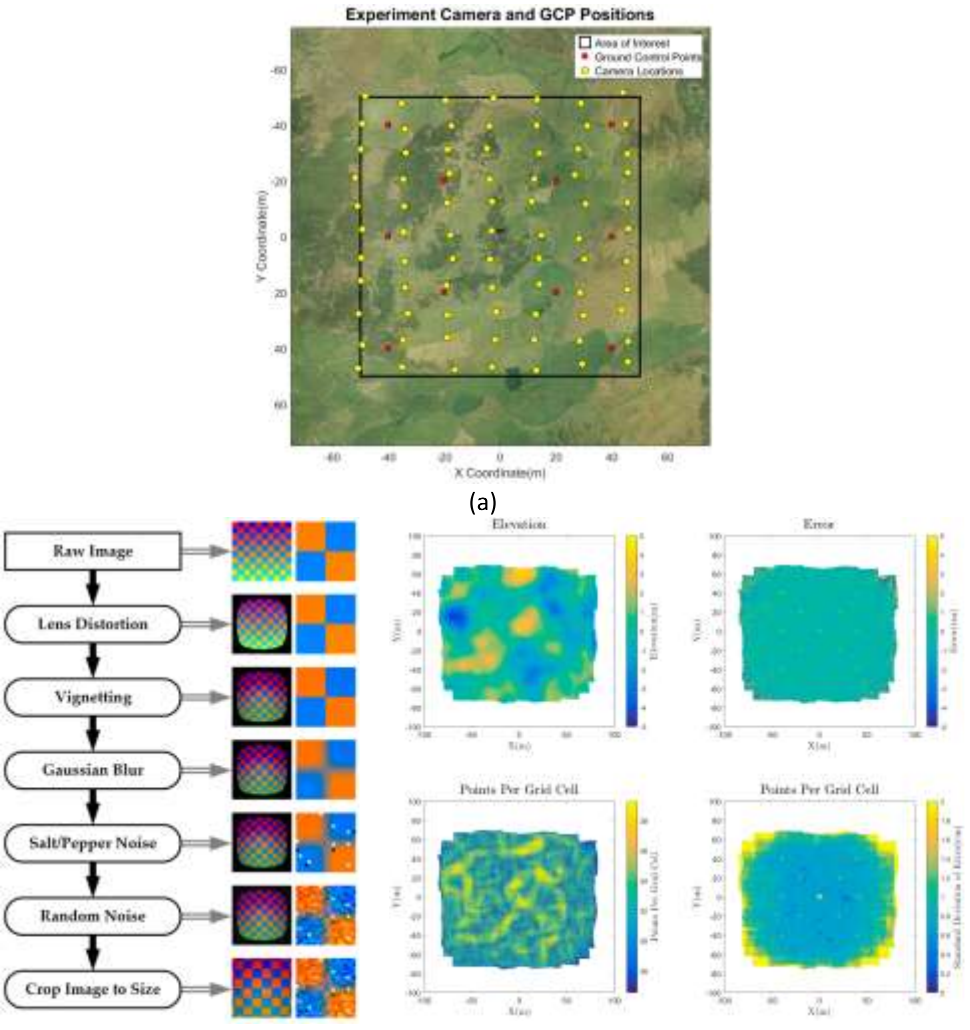
4.1 Utilizing Open-Source Tools for Precision Geometry Modeling in CFD

Constructing precise and refined model geometry is fundamental in CFD simulations, serving as the foundation for meshing and subsequent analytical tasks. The efficacy of these simulations heavily relies on acquiring meticulously prepared and refined CAD files, which detail essential geometry descriptions for prescribing accurate physical conditions and facilitating controlled meshing. Simplification and error removal are integral in focusing on the fluid flow in the spaces between solid objects and mitigating unnecessary complexities, especially in intricate components. Creating geometrical models that are compatible with CFD meshing frequently becomes a lengthy and challenging part of the CFD analysis process. It is essential to accurately depict the actual system to efficiently produce a computational grid. This grid is a key element in CFD simulations, as it needs to be sufficiently detailed to capture all relevant scales for the specific issue being addressed, yet not overly detailed to avoid excessively increasing the computation time [16].

In the spectrum of tools facilitating advanced modeling and meshing, OpenVSP (Open Vehicle Sketch Pad), distinguishes itself as an open-source parametric aircraft geometry tool, initially developed by NASA [17-20]. This tool is designed to create 3D models of aircraft and to support the engineering analysis of these models. It permits users to quickly translate ideas into computer models that can be further analyzed, proving invaluable for generating and evaluating unconventional design concepts. OpenVSP offers a multitude of basic and advanced geometries common to aircraft modeling, which users modify and assemble to create models. Alongside geometry modeling, OpenVSP encompasses a variety of tools, including CompGeom and VSPAERO, aiding in aerodynamic or structural analysis of models [18]. It allows importing and exporting of various geometry formats like STL, CART3D (.tri), and PLOT3D, enhancing its utility in mesh generation and in CFD or FEA software.

Among other notable tools are FreeCAD, a considerable alternative to commercial CAD packages; OpenSCAD, known for enabling the creation of accurate 3D models and parametric designs through script-based modeling; and Blender, recognized for its robust 3D modeling engine [21-30]. Wings 3D is pivotal for learning 3D modeling basics with its advanced subdivision modeling techniques, while SketchUp serves as an ideal starting point for architectural modelling [31-33]. Onshape offers collaborative, cloud-based 3D modeling solutions, and MeshLab provides extensive features for processing and editing 3D triangular meshes [34-38]. Lastly, SALOME stands out as a versatile platform, encompassing a broad spectrum of applications from 3D modeling to post-processing in various industrial sectors [39-41]. Figure 4 shows one such example of usage of Blender for UAS-Based Photogrammetry [42]. Additionally, BRL-CAD is an open-source, cross-platform solid modelling system that includes a suite of tools for geometry editing, ray-tracing, image and signal processing, among others [43,44]. Finally, SolveSpace is identified as a user-friendly parametric 3D CAD program, offering both 2D sketching and 3D modelling with a focus on constraint-based modelling [45,46].

These tools, each with its own unique capabilities and distinctive functionalities, play an instrumental role in streamlining the intricate tasks of geometry construction, modelling, and meshing in CFD simulations. They ensure the simplification and optimization of intricate geometries, efficient management of computational resources, and accuracy in the representations of physical systems. By integrating accurate geometric modelling with advanced meshing solutions provided by these tools, professionals can achieve highly refined and precise simulations, marking them as indispensable entities in contemporary engineering landscapes.



(a)

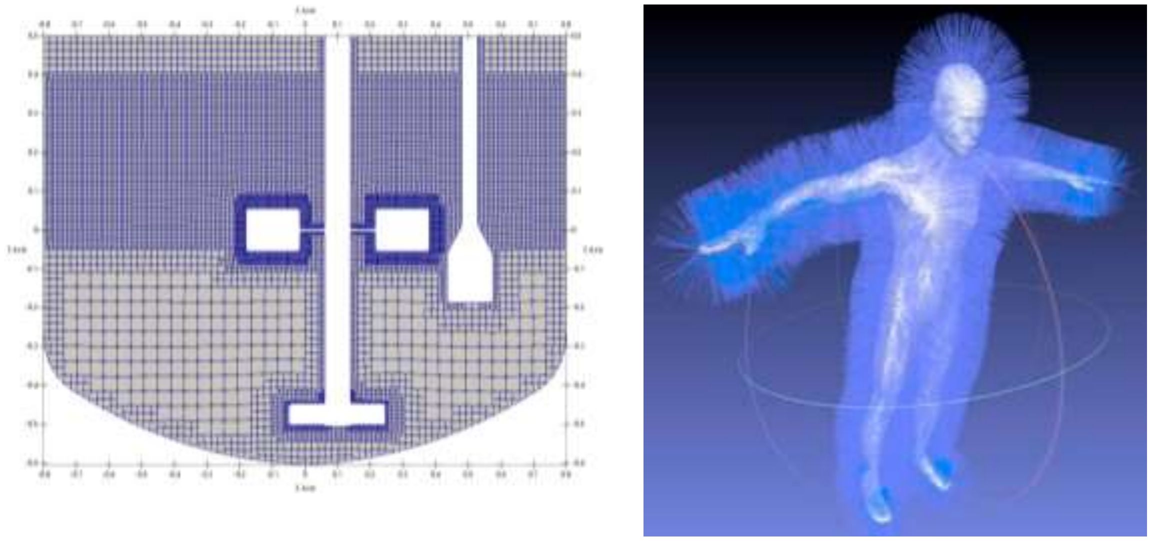
(b) (c)

Fig. 4. (a) Experimental Photogrammetry (b) Blender imagery rendered using pin hole camera model (c) Binning gridding algorithm and its usage in visualizing errors and PPGC [42]

4.2 Meshing Techniques and Open-Source Tools in Computational Simulations

Meshing is crucial in software-based simulations like Finite Element Analysis (FEA) and, more prominently, in CFD as it influences the simulations' accuracy and resource demands [47,48]. In CFD, the mesh quality often dictates the model's efficacy, impacting convergence, memory needs, and solution precision. A robust mesh must avoid void regions and overlapping elements while maintaining high quality, sufficient resolution, and minimal computational cost. The structured and unstructured meshing techniques allow for precise transformations of continuous geometric entities into definable shapes, adapting to intricate designs with varying regularity. Modern meshing tools, many of which are open-source, have provisions for automatic checks or offer solutions to detect and amend transgressions in mesh creation, ensuring the absence of elements with zero or negative volume that render the equations extremely challenging to solve. They focus on optimizing the aspect ratio, mitigating skewness, and controlling growth rate, which is critical for maintaining local accuracy and manageable equation conditions, particularly when transitioning from high-aspect-ratio elements to isotropic elements in areas like boundary layer meshes. These optimizations are vital for maintaining solid and watertight mesh geometries in fluid flow simulations, enabling solvers to identify the correct flow domain and facilitating precise assignments of governing equations to distinct cells. Such meticulous approaches to meshing are imperative for achieving a balanced, efficient, and accurate representation in numerical analyses, particularly in areas subjected to significant stress or located in the load path, ultimately advancing the comprehensive capabilities of computational simulations in varied scientific domains.

It is here that software tools like Netgen/NGSolve and Gmsh become pivotal, providing high-performance solutions and seamless integrations for analyzing models from solid mechanics to electromagnetics [41,49-54]. Netgen/NGSolve is renowned for its flexible Python interface and seamless integration from geometric modeling to visualization [55]. In contrast, Gmsh serves as a 3D finite element mesh generator, emphasizing a user-friendly and modular approach with efficient interactions with Netgen for mesh adaptations [56,57]. Additionally, the CFD General Notation System (CGNS) focuses predominantly on compressible viscous flow data, serving as a standard for data storage and retrieval in CFD analysis, enabling data exchange and archiving of aerodynamic data [58-61]. SALOME, a comprehensive open-source scientific computing environment, integrates physics solvers and offers modules accessible through GUI and Python scripts. CalculiX, another notable software, provides extensive support and integration options, hosting implicit and explicit solvers and offering functionalities analogous to commercial FEM programs like Abaqus [62]. Solutions like Overture, specializing in solving partial differential equations (PDEs), and OpenFOAM, providing premier open-source mesh tool suitable for varied complexities, contribute to a diversified and flexible software development environment for simulating physical processes in intricate moving geometries [41,63-68]. Lastly, enGrid, designed specifically for CFD applications, emphasizes mesh generation and supports automatic prismatic boundary layer grids for Navier-Stokes simulations [69-71]. Each tool, with its unique characteristics, contributes to establishing a comprehensive ecosystem for CFD and FEA, advancing multiple scientific domains with their open-source nature, versatility, and extensive capabilities, thus underlining the importance of the meshing process in the realm of computational simulations and mechanics. Figure 5(a) and Figure 5(b) show the OpenFOAM-based BlockMesh and MeshLab as open-source grid tools, respectively [72].



(a) (b)

Fig. 5. (a) Meshing of an industrial reactor model in OpenFOAM BlockMesh, (b) Surface normal of a model in MeshLab [73,74]

4.3 Open-source CFD Solvers

In the realm of CFD modeling, the preliminary steps of preparing the geometry and creating the mesh are fundamental. It is paramount to choose the appropriate models to accurately represent the problem's physics, be it through transient or steady-state simulations, based on the flow's spatial or temporal variations. CFD solvers are software tools designed for simulating fluid flow and related phenomena using numerical methods and algorithms, mainly solving the Navier-Stokes equations. They are capable of addressing a variety of issues like airflow around objects, heat transfer, turbulent flows, and fluid-based chemical reactions. The process involves three stages: pre-processing (defining the problem and preparing the computational domain), solving (numerical solution of the equations), and post-processing (analysis and visualization of results). The effectiveness of a CFD solver is influenced by the model's complexity, the discretization methods used (like finite volume or finite element), and the available computational resources. Different solvers are tailored for specific types of problems, with some being better suited for incompressible flows and others for compressible or multiphase flows. The choice of solver depends on the specific needs of the problem, including flow regime, geometric complexity, and the required detail in the outcomes.

CFD software packages are generally categorized into CAD Embedded (SolidWorks Flow Simulation, Autodesk CFD, and ANSYS Discovery Live), Open-Source (OpenFOAM, SU2, MFIX and SimScale), Semi-Comprehensive (COMSOL CFD, CONVERGE CFD and NUMECA OMNIS), and Comprehensive (Simcenter STAR-CCM+ and ANSYS Fluent) shown in Figure 6 [75].

OpenFOAM is particularly noteworthy as a C++ toolbox, acclaimed for its versatility in solving a plethora of continuum mechanics problems, including complex fluid flows involving chemical reactions, turbulence, heat transfer, acoustics, solid mechanics, and electromagnetics. This software finds extensive application in numerous industries and academic institutions, endorsed by its vast user base. Similarly, other open-source software like SU2, Code_Saturne, Gerris, COOLFluiD, FreeFEM, OpenFVM, ReFRESCO, and TrioCFD, each with its unique features and capabilities, caters to diverse needs in the computational fluid dynamics landscape [76-94]. They range from solving the Navier-Stokes equations for various flows in Code_Saturne to providing a powerful component-based framework for high-performance computing in COOLFluiD [95].

Fig. 6. CFD software packages

Each piece of software serves as a cog in the extensive machinery of computational fluid dynamics, contributing to the sophisticated simulation of fluid flows in varied domains. In the realm of CFD, over a thousand solvers have been developed by global research entities and laboratories. These solvers are predominantly available for non-commercial utilization under the General Public

License. For instance, FluidX3D emerges as a distinct CFD software, excelling in lattice Boltzmann methods [96-100]. Renowned for its speed and efficient memory usage, it operates on all GPU platforms via OpenCL [101]. Created by Moritz Lehmann, FluidX3D is free for non-commercial purposes, aligning with educational, research, and amateur applications. Additionally, FLOWUnsteady presents itself as an open-source, variable-fidelity framework for unsteady aerodynamics and aeroacoustics [102]. It is based on the reformulated vortex particle method (rVPM), a brainchild of the FLOW Lab at Brigham Young University [103]. PALABOS, focusing on lattice Boltzmann methods, is adept in simulating fluid flows in intricate geometries and multiphase conditions [104,105]. Nektar++, a spectral/hp element framework, addresses a broad spectrum of scientific and engineering challenges, encompassing fluid dynamics and wave propagation shown in Figure 7 [106-108]. FEniCSx, though not solely a CFD solver, offers a comprehensive suite of free software for solving partial differential equations (PDEs), inclusive of fluid dynamics challenges [109-114]. CFDTool, a MATLAB-based toolbox, simplifies the learning of fluid dynamics basics, targeting educational and basic commercial applications [115-118]. Elmer, a multi-physics simulation software, integrates fluid dynamics with structural mechanics, electromagnetism, and heat transfer, making it suitable for coupled multi-physical problems [119-121]. BARAM, an open-source CFD software, is designed to streamline the learning process for text-based solvers, featuring a user-friendly graphical interface and incorporating OpenFOAM® solvers modified by NEXTFOAM under GPL [122-124]. The University of Liverpool's Solver, also under GPL, serves an educational purpose in CFD, encompassing Euler equations, Roe's solver, Harten's entropy correction, and other features for both steady and unsteady flows [125]. UCNS3D, an open-source solver for compressible flows on unstructured meshes, employs high-order methods apt for industrial-scale CFD challenges [126]. The HOS Solvers, released under GPLv3, play a pivotal role in naval engineering by facilitating nonlinear irregular wave generation in CFD, crucial for assessing loads on offshore structures [127,128].

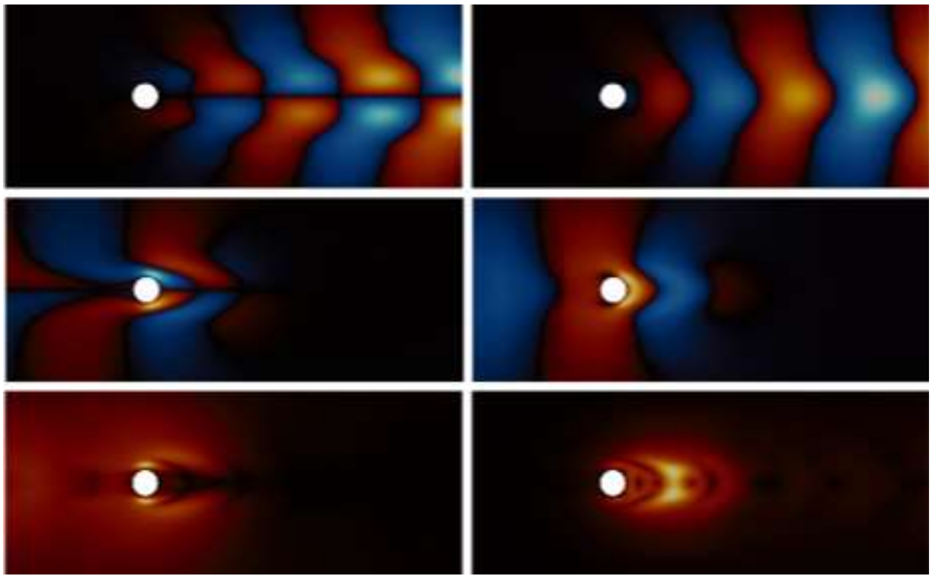


Fig. 7. Linear stability analyses of two-dimensional flow past a circular cylinder at $Re = 4$ in Nectar++ [106]

The compilation from Simon Wenkel's website adds other notable solvers like deal.II, Gerris, and Kratos Multiphysics [129-134]. deal.II, an open-source library, is instrumental in solving PDEs using finite element methods, primarily in computational science and engineering. Gerris, a flow solver, is recognized for its proficiency in managing complex geometric domains with adaptive mesh refinement. Kratos Multiphysics, an opensource framework, is acclaimed for its adaptability in handling diverse physical processes in computational simulations.

Flowsquare is a two-dimensional CFD software ideal for analyzing both unsteady and reactive/nonreactive fluid flows, including subsonic and supersonic flows [135,136]. Flowsquare is designed for ease of use and aims to make CFD technology more accessible for academic and educational purposes. It does not require expertise in meshing, programming, CAD, or pre/post-processing, allowing for straightforward simulation setups using bitmap images and text files. Flowsquare is used globally by individuals, companies, and educational institutions for various purposes.

APHROS is a finite volume solver, excels in simulating incompressible multiphase flows with surface tension, making it ideal for complex geometries and interactions between immiscible fluids [137,138]. hyStrath, another C++ code, is tailored for hypersonic and rarefied gas dynamics and is GPL-3.0 licensed [139,140]. FourierFlows.jl utilizes Julia to create adaptable pseudospectral solvers for partial differential equations [141,142]. Flow, by NVIDIAGameWorks, is a C-based library for real-time fluid simulation in sparse grid setups [143,144]. PteraSoftware, a Python package, is designed for the analysis of flapping-wing flight, offering speed and ease of use [145,146]. Nalu, leveraging the Sierra Toolkit and Trilinos solver stack, is a versatile, unstructured low Mach flow code suitable for a range of applications [147-149]. FluidFoam enhances OpenFOAM postprocessing with its Python-based tools. Incompact3d, developed in Fortran, optimizes Navier-Stokes equation solutions for current CPU architectures [150-152]. The 2d-fluidsimulator, implemented in Taichi and Python, handles 2D incompressible fluid dynamics. Lastly, MagIC, a high-performance Fortran code, adeptly solves magneto-hydrodynamics equations in rotating spherical shells [153]. Each solver has its unique strengths and suitability for particular CFD problems, influenced by factors like geometric complexity, flow nature, the necessity for multi-physics coupling, and computational resource availability.

4.4 Open-source Post-processors in Computational Simulations

In the process of CFD analyses, post-processors serve as software tools that scrutinize, interpret, exhibit, and make sense of simulation outcomes. They transform the extensive data produced by CFD simulations into visual formats such as graphs, charts, or thermal mappings, varying with the software used. Engineers and scientists can uncover trends, understand fluid flow dynamics, and make informed decisions with these post-processing tools. Certain CFD solvers, including OpenFOAM, SU2, and Gmsh, are equipped with integral post-processors [75,76,78]. The post-processor in Gmsh can be augmented with custom plug-ins that modify existing visualizations or generate new perspectives based on the existing data.

ParaView is an open-source application extensively utilized for CFD simulations, founded on the Visualization Toolkit (VTK) [39,154-156]. It facilitates Python scripting scripting and batch processing for efficient operations as shown in Figure 8 [157]. VisIt offers various visualization techniques, including contour plots, volume rendering, 2D and 3D visualization as shown in Figure 9, for presenting complex data [158-162]. It handles both time-varying and structured data, allowing users to dissect specific areas or time intervals within datasets. VisIt supports numerous data formats used in scientific and technical domains, such as VTK, HDF5, NetCDF, and others [163-165]. It can immediately read data from experiments or simulations. OpenDX, MayaVi, and GNUplot represent a selection of the accessible open-source post-processing software solutions [166-168].

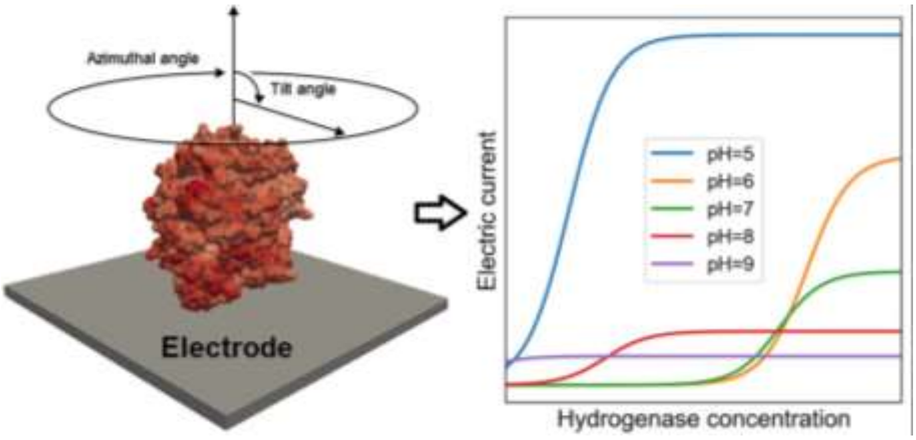


Fig. 8. ParaView visualization of electrostatic interaction and catalytic activity of [NiFe] hydrogenases on a planar electrode [169]

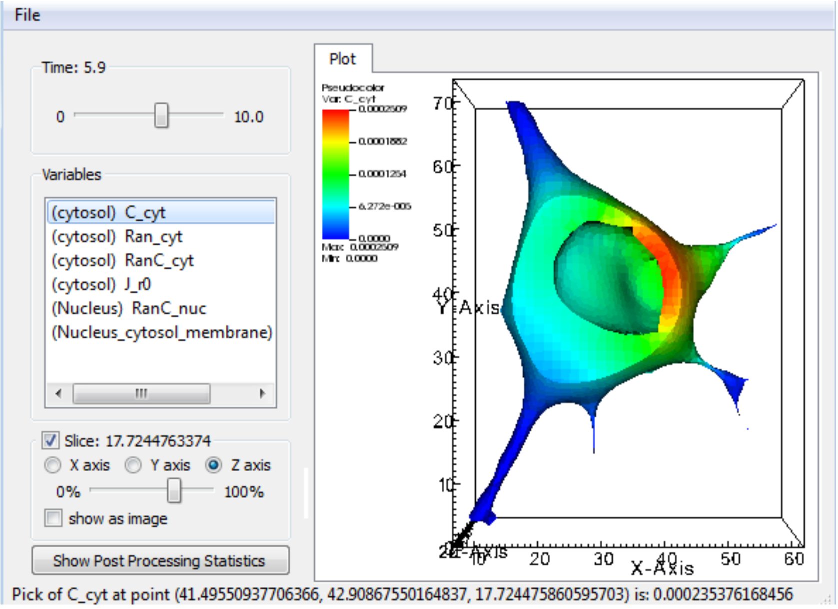


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Fig. 9. A glimpse of the VisIt post-processing tool GUI [170]

Mayavi2 which is part of the Mayavi Project, utilizes Python to display scientific data, offering a range of capabilities for 3D scientific data visualization and plotting [171]. On the other hand, the highly scriptable GNUplot is a portable, command-line-driven, open-source tool for creating various types of charts and graphs, making it versatile for data visualization [172,173]. Open-source tool ENigMA implements several capabilities such as Mesh generation, post-processing, STL file processing, Smoothed Particle Hydrodynamics (SPH), PDEs, FEM, FVM, FDM, etc [174,175].

SimWorks, a complimentary CFD software, incorporates a unified GUI for OpenFOAM, the renowned open-source software pivotal for meshing and solving tasks in CFD [176,177]. Its capabilities span across multiple CFD analytical stages, encompassing geometry inspection, pre-processing, meshing, case setup, solving, and post-processing. Concurrently, Cassiopee, an innovation by ONERA, emerges as another open-source software that consolidates pre- and post-processing tools within a singular platform [178]. This integration aims to streamline various CFD analytical components, thereby offering a holistic solution that addresses both initial and final stages of CFD investigations. Additionally, Octave, as an open-source scientific programming language, positions itself as a MATLAB alternative, adept at executing a range of scientific computations, including those related to CFD data analysis and visualization [179,180].

4.5 Open-source Post Data Generation and Availability

Computational Fluid Dynamics (CFD) simulations generate vast amounts of data, and making this data available to the scientific community is crucial for collaboration, validation, and further research. Commercial software such as ANSYS Fluent, COMSOL Multiphysics, and Siemens STAR-CCM+ are widely used for CFD simulations in various industries. These tools offer advanced solvers, pre-processing, and post-processing capabilities. Open-Source CFD Software like OpenFOAM, SU2, and FEniCS are popular open-source CFD software. They provide flexibility and customization, making them widely adopted in academic and research settings. Many CFD simulations require significant computational resources. HPC clusters and supercomputers are often used to perform large-scale simulations.

The platforms for hosting this massive amount of data are 1. Institutional Repositories: Universities and research institutions often have their own data repositories. Institutional repositories may use platforms like DSpace, Figshare, or Dataverse to store and share CFD data 2. Public Data Repositories: Public repositories such as Zenodo, Dryad, and DataCite accept CFD data submissions. These platforms provide Digital Object Identifiers (DOIs) for datasets, ensuring proper attribution and citation 3. Collaborative Platforms: Collaborative platforms like GitHub and GitLab are commonly used for sharing not only code but also input files, simulation setups, and post-processing scripts. These platforms facilitate version control and collaborative development 4. Domain-Specific Repositories: Some disciplines have specific repositories for CFD data. For example, all the subscription and Open-Source CFD International Journal encourages authors to provide data along with their publications 5. Journals and Conference Proceedings: CFD data can be published as supplementary material in scientific journals or conference proceeding. This allows researchers to share the data alongside their findings.

However, this comes with certain challenges and considerations. For instance, data privacy and sensitivity. Depending on the nature of the simulations, there may be privacy or proprietary concerns. Care must be taken to anonymize or exclude sensitive information. Another issue is about data format and metadata. Standardizing data formats (e.g., HDF5, NetCDF) and providing detailed metadata enhance the usability of the shared CFD data. Researchers should specify the licensing terms for the shared data, ensuring proper attribution and adherence to copyright policies. Large datasets may pose challenges for storage, transfer, and download. Consideration should be given to the scalability of hosting platforms. Ensuring long-term accessibility and preservation of CFD data is essential. Repositories with sustainable funding and archiving practices are preferable. So, the availability of CFD data relies on a combination of suitable tools for simulation and appropriate platforms for data hosting. Open-access repositories, collaborative platforms, and domain-specific repositories contribute to the dissemination of CFD data, fostering collaboration and advancing scientific knowledge in fluid dynamics [181].

4.6 Reproducibility Problem in CAE Applications

Reproducibility issues in Computer-Aided Engineering (CAE) applications can pose significant challenges for researchers and the broader scientific community. These problems often arise due to the lack of sharing source code, difficulties in submitting changes to mainstream repositories, and the resulting need for researchers to reinvent solutions. Here are some key aspects contributing to these challenges:

(i) Closed-Source Nature of CAE Software

Many CAE applications are proprietary and closed-source, restricting access to the underlying code. This makes it difficult for researchers to understand, modify, or extend the software to address specific needs or improve its functionality

(ii) Difficulty in Submissions to Mainstream Repositories

Submitting changes or improvements to mainstream software repositories can be challenging for several reasons. The development processes of established software projects may be rigid, making it difficult for external contributions to be accepted. Additionally, legal and licensing issues may further complicate the integration of external code into existing projects.

(iii) Lack of Documentation

Even when researchers are willing to share their code, the lack of comprehensive documentation can hinder reproducibility. Incomplete or unclear documentation makes it difficult for others to understand and use the code effectively.

(iv) Funding and Time Constraints

Researchers may face constraints in terms of funding and time, which can limit their ability to share code, document their work thoroughly, or contribute to mainstream repositories. These constraints contribute to the challenges of reproducibility in the CAE domain.

(v) Limited Code Sharing

In the CAE community, there is often a lack of culture surrounding the sharing of source code. Researchers may be hesitant to share their code due to concerns about intellectual property, competition, or simply because they have not prioritized making their code publicly available.

(vi) Versioning and Compatibility Issues

CAE applications often involve complex dependencies on hardware, libraries, and other software components. This can lead to versioning and compatibility issues, making it challenging to reproduce results when different versions of the same software or its dependencies are used.

(vii) High Computational Requirements

CAE simulations often require significant computational resources, including specialized hardware and software configurations. This makes it difficult for researchers with limited resources to replicate and validate the results obtained by others.

To address these issues, fostering a culture of openness, collaboration, and code sharing within the CAE community is crucial. Encouraging researchers to provide clear documentation, use open-source licensing, and actively contribute to relevant repositories can significantly enhance the reproducibility and transparency of CAE research. Additionally, efforts to develop community-driven standards for code sharing and integration could help streamline the process of submitting changes to mainstream repositories [182].

4.7 Advantages and Disadvantages of OS Software

Open-source CFD software has gained popularity due to its accessibility, flexibility, and collaborative nature. However, like any technology, it comes with its own set of advantages and disadvantages from a user perspective. Table 2 below shows the advantages and disadvantages of open source software.

Table 2
Pros and cons of open-source entities and their details

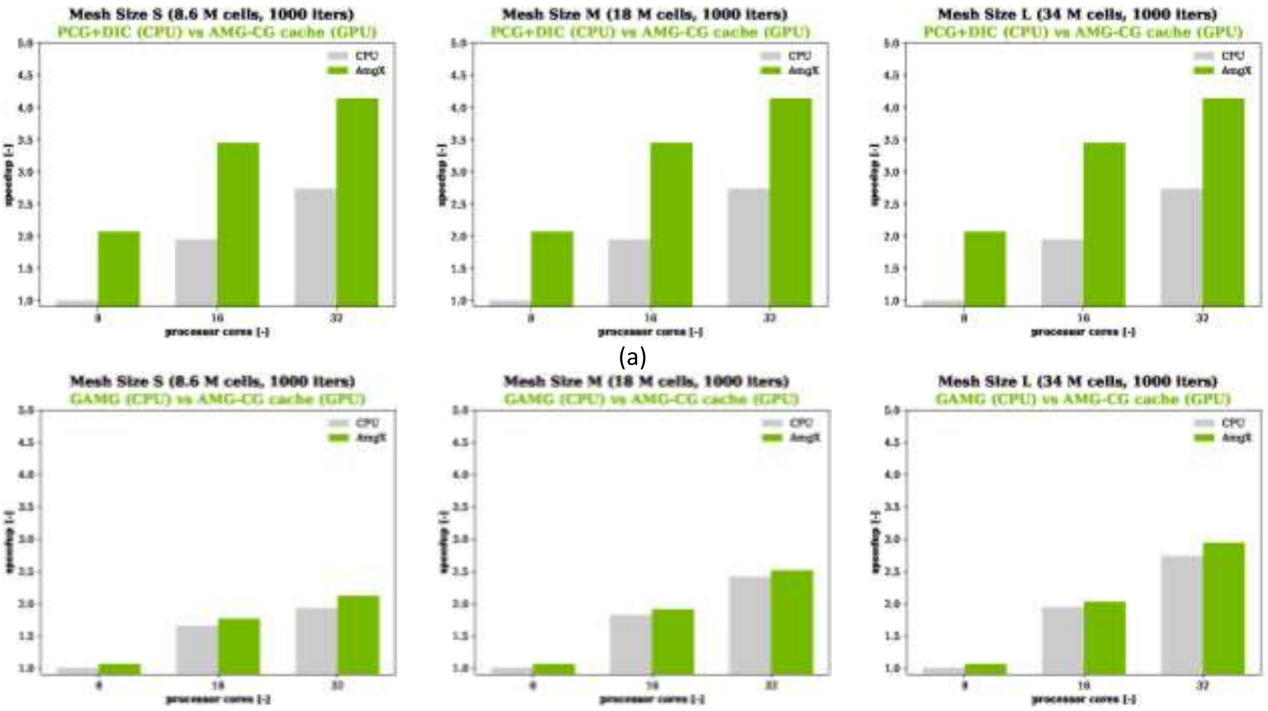
Advantages	Disadvantages
Cost: One of the most significant advantages is cost savings. Open-source software is typically free to download and use, making it an attractive option for individuals, academic institutions, and small businesses with limited budgets.	Limited User Interface and Documentation: Open-source CFD software may lack a user-friendly interface compared to commercial counterparts. Additionally, documentation may not be as comprehensive or accessible, which can steepen the learning curve for new users.
Flexibility and Customization: Users have the freedom to modify and customize the source code according to their specific needs. This level of flexibility is particularly beneficial for researchers and developers who want to tailor the software to their unique requirements.	Support and Training: While there is a community for support, it may not be as responsive or comprehensive as dedicated customer support from a commercial software vendor. Users may find it challenging to get timely assistance for specific issues.
Community Support: Open-source CFD software often has a large and active community of users and developers. This community support can be invaluable when seeking help, troubleshooting issues, or collaborating on the improvement of the software.	Integration Challenges: Integrating open-source CFD software into existing workflows or with other software tools may pose challenges. Compatibility issues and the need for additional customization can require extra effort.
Continuous Development and Updates: With a large community contributing to the software, updates and improvements are frequent. Users can benefit from the latest features, bug fixes, and enhancements without relying solely on the development roadmap of a commercial vendor.	Commercial Code Features: Some advanced features found in commercial CFD software may not be available in open-source alternatives. Users with specific requirements may find that certain capabilities are only provided by proprietary solutions.
Transparency: The open nature of the source code provides transparency, allowing users to understand how the algorithms work. This transparency is essential for research purposes and for building trust in the accuracy and reliability of the simulations.	Stability and Validation: Open-source software may undergo rapid development, leading to potential instability in certain releases. Additionally, the lack of strict validation processes compared to commercial software may raise concerns about the accuracy of results in critical applications.

5. Role of AI-ML-DL and High-performance Computing in CFD using Open-source Tools

Traditional computational fluid dynamics (CFD) methods involve solving partial differential equations governing fluid flow behavior using numerical techniques. However, these methods encounter difficulties in handling complexities such as intricate geometries, turbulent flows, and multi-physics interactions. The integration of Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) techniques into CFD workflows offers promising solutions to these challenges, unlocking new capabilities in fluid dynamics simulations. Open-source tools and software platforms provide accessible and customizable environments for implementing and experimenting with AI-driven approaches in CFD simulations.

In addition to software like SimScale based on cloud computing (with free access for limited hours nearly one time 3000 computational hours and 500 GB storage) compared to commercial options like Ansys, open-source high-fidelity codes have been utilized for various applications ranging from reconfigurable systems to intricate problems like insect aerodynamics, flow topology and bird flapping kinematics and aerodynamics [183-188]. AI and ML algorithms play a crucial role in enhancing turbulence modelling by leveraging large datasets of experimental or high-fidelity simulation results. Techniques such as neural networks excel in capturing complex flow features, leading to more accurate turbulence closure models [189].

DL-based surrogate models offer an alternative to computationally expensive CFD simulations for tasks such as parameter optimization, sensitivity analysis, and uncertainty quantification. These surrogate models provide faster evaluations while maintaining acceptable accuracy levels. AI algorithms automate complex geometries and meshing processes, reducing manual intervention and enhancing efficiency. DL methods, like generative adversarial networks (GANs), can generate realistic geometries based on specified design criteria [189]. ML techniques enable real-time flow control and optimization by learning from simulation data and adjusting control strategies accordingly. Reinforcement learning algorithms optimize parameters to achieve desired flow characteristics or performance metrics. AI-driven approaches detect anomalies in CFD simulations and rectify errors to enhance reliability and robustness. ML models trained on historical simulation data can identify discrepancies and propose corrective actions during runtime [190]. Various open-source tools and software platforms facilitate the integration of AI, ML, and DL techniques into CFD simulations. For example, using dynamic mode decomposition which is a machine learning based reduced order modeling technique or using neural networks and sparse algorithms for accelerated CFD [190]. OpenFOAM, for instance, supports customization and extension for implementing AI-driven algorithms. TensorFlow, PyTorch, scikit-learn, and Keras are popular frameworks for building and training neural networks and machine learning models in Python. Additionally, SU2 and other high-fidelity open-source CFD codes offer capabilities for adjoint-based optimization and uncertainty quantification, compatible with ML integration. Some of these open source codes for complex problems need high computational facility like GPU platforms to get excellent results as shown in Figure 10 [191]. Thus, the integration of AI, ML, and DL techniques revolutionizes the field of computational fluid dynamics, addressing challenges and unlocking new possibilities for simulation accuracy, efficiency, and automation. Open-source tools and software platforms democratize access to these advanced techniques, fostering collaboration and innovation in the CFD community. The era of relying on conventional methods for tackling straightforward tasks, for example like MHD stream based analysis or modified shape FSI is behind us [192,193]. Now, with open-source tools readily available, even the most intricate problems can be effortlessly addressed, devoid of concerns about commercial constraints.



(a)

(b)

Fig. 10. Scalability calculated across three tested grids (S, M, L). (a) PCG-DIC (CPU) vs. AMG-PCG (GPU) and (b) GAMG (CPU) vs. AMG-PCG (GPU) [191]

6. Conclusions

This article has conducted a thorough review of the myriads of open-source tools available for Computational Fluid Dynamics (CFD) and their significant role in propelling research in fluid dynamics. These tools, which range from advanced geometry modeling to sophisticated post-processing software, are not just alternatives to their commercial counterparts but are pivotal in democratizing advanced computational capabilities. By providing cost-effective, customizable, and transparent solutions, open-source tools are reshaping the CFD landscape, making it more accessible to a broader audience. They facilitate a culture of openness and collaboration, encouraging innovation and knowledge-sharing among researchers and practitioners. This is in line with the growing global movement towards open science, where transparency, reproducibility, and communal progress are at the forefront. As CFD continues to evolve, the adoption of open-source tools will undoubtedly play a crucial role in the sustainability and expansion of this field, ensuring that the scientific community can collectively tackle more complex and nuanced fluid dynamics challenges. This paper is exclusively focused on the analysis of incompressible open-source software, excluding considerations for compressible counterparts. It is important to note that there exist open-source codes designed to handle compressible flow scenarios as well. However, we intend to explicitly highlight the inherent incompressibility of the software under examination, providing a clearer understanding of their capabilities.

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Conflict of Interest

Authors declare no conflict of interest.

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