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Systematic Review of Computational Fluid Dynamics Modelling and Simulation Techniques Employed in Vertical Axis Hydrokinetic Turbines

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ABSTRACT

At present, Computational Fluid Dynamics (CFD) is being utilized to explore tidal and hydrokinetic turbine systems, advancing comprehension of turbulent flow phenomena and raising the accuracy of performance predictions for these fluid-driven turbines. Consequently, this utilization of CFD contributes to the optimization of efficiency in these devices. Turbines are subject to variations from the best design point due to the influence of fluctuating flow rates, despite the findings of recent research that have identified the ideal design points. In contrast to conventional literature reviews, systematic analysis offers numerous advantages. The methodological strategy applied in this study entailed cross-referencing the findings obtained from Web of Science (WOS) and Scopus databases to establish the comprehensiveness as well as reliability of researcher data. Improving the review process, elevating the prominence of the field of study, and establishing critical priorities to mitigate research bias are all potential strategies for enhancing the quality of these evaluations. This research divides its findings into three core themes: (1) Performance assessment for practical implications, (2) Numerical analysis for theoretical insights, and (3) Design parameter optimization for engineering relevance. These themes collectively provide a well-rounded examination of the research outcomes across practical, theoretical, and engineering dimensions. Finally, the research findings have the potential to act as a significant point of reference for informing the best design considerations pertaining to vertical axis turbines.

1. Introduction

The harnessing of renewable energy sources has emerged as a pivotal component of global efforts to mitigate climate change and ensure sustainable energy access [1–3]. Among the myriad renewable energy technologies, Vertical Axis Hydrokinetic Turbines (VAHKTs) [4–7] stand as a promising and innovative approach to tapping into the kinetic energy of water currents. These turbines exhibit unique advantages, such as lower maintenance requirements and suitability for

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installation in a wide range of water environments, making them a compelling choice for clean energy production. To maximize their efficiency and applicability, Computational Fluid Dynamics (CFD) [8], [9] has emerged as an essential instrument in assessing and analyzing VAHKTs performance. In this systematic review, we delve into the extensive body of research on CFD techniques applied to VAHKTs, aiming to present a comprehensive synthesis with regard to the present state of knowledge, identify trends, and highlight gaps in the field.

VAHKTs, in this case, shown in Figure 1, represent a transformative technology with the potential to revolutionize the renewable energy landscape [10–12]. Unlike their horizontal axis counterparts, VAHKTs [13–15] possess inherent design advantages, including omnidirectional rotor orientation and enhanced adaptability to varying water flow conditions. However, successfully deploying and optimizing VAHKTs necessitate a deep understanding of the complex fluid dynamics [16,17] that govern their operation. CFD, a branch of computational engineering, offers a robust platform for simulating and analyzing the intricate interactions between fluid flow and turbine performance. This review seeks to elucidate the pivotal role of CFD in advancing our comprehension of VAHKTs, exploring the various modeling approaches, simulation techniques, and associated challenges encountered in the pursuit of efficient and sustainable energy generation from water currents.

As the urgency to transition towards clean and sustainable energy sources intensifies, it becomes imperative to critically assess the current state of research on VAHKTs and CFD applications. By synthesizing the vast body of literature, this systematic review aims to facilitate knowledge dissemination, highlight areas of consensus, and pinpoint research gaps. Moreover, it aims to function as a valuable tool for engineers, researchers as well as policymakers engaged in the deployment and development of VAHKTs. The authors aim to contribute to the informed decision-making and innovation necessary to drive the sustainable energy transition forward by elucidating the key findings and methodological approaches in this dynamic field.

2. Literature Review

Lewis & Cimbala describe CFD simulations as demonstrating a notable enhancement in turbine efficiency during off-design operation by implementing a distinctive guide vane design. This novel concept has the potential to mitigate rotor-stator interactions [18]. One of the most significant current discussions on CFD techniques was conducted by Sutikno *et al.,* [19]. In 2019, Unterluggauer *et al.,* conducted a study wherein they expounded upon the significance of CFD and numerical techniques in facilitating hydropower plant operators' comprehension of key operation zones and evaluation of fatigue damage. [20]. The study conducted by Zhou used CFD to effectively simulate the dynamic behavior with regard to floating offshore wind turbines, demonstrating the minimal influence of wave type as well as steepness on turbine performance [21]. In initial research conducted by Chen, a vertical-axis water turbine was designed for capturing hydropower from water pipelines, providing small-scale power for data gathering and maintenance operations, offering insights for improving water supply management, and ensuring uncontaminated water [22]. The study utilizes CFD to study the fluid field of turbines, highlighting the significance of fluid turbulence in turbine design and demonstrating the accuracy of high-resolution advection schemes [23].

The results of this research will offer an overview of their design, utilization, and performance characteristics, with a specific emphasis on a reduced-scale model appropriate for micro-scale Pumped Hydro Energy Storage (PHES) applications [24]. The study by Zamora-Juárez *et al.,* suggests that the integration of a micro hydropower station into a rainwater collecting system is an effective approach. This evaluation will be conducted through CFD analysis, identifying the most suitable dimensions for the turbine design [25]. This is substantiated by Darsono *et al.,* who employed CFD techniques to assess the effectiveness with regard to a water bulb-turbine in a water conduit system, examining how flow rate and velocity affect its efficiency. The findings indicate a positive correlation between flow rate and efficiency, whereby efficiency consistently rises as flow rate increases [26]. In a different study, Kamal & Saini explore the performance of a hydrokinetic turbine, focusing on its modifications and enhancements. This work utilizes CFD parameters to devise as well as improve a cross-flow hydrokinetic system, with the ultimate goal of mitigating the ecological consequences associated with the utilization of fossil fuels [27]. With the same objective, Prabowoputra *et al.,* conducted a numerical investigation of hydro energy employing a CFD technique known as the three-dimensional CFX Solver on ANSYS software. This approach is utilized to examine hydro-turbines of the cross-flow variety [28].

Praveen Kumar thoroughly analyzed Pelton turbines' fluid dynamics, as shown in Figure 2, and the characterization of their lightweight materials [29]. In another study, Tarodiya *et al.,* examined the areas of hydro-abrasive erosion that are of utmost importance in Pelton turbines that operate under conditions involving the presence of silt in the water. This work offers valuable engineering insights on managing erosion and jet breakage concerns in Pelton turbines [30]. However, the study focuses on developing a micro-hydroelectric power facility using low-pressure water flow. The turbine, Kaplan-type, transforms water energy into electrical energy. CFD analysis reveals the turbine's highest power output at maximum head [31]. In their study, Prabowoputra *et al.,* conducted a quantitative analysis with regard to the Savonius water turbine. They converted a one-stage rotor into a two-stage structure and utilized ANSYS codes for testing. The simulation employs Transient Blade Row analysis methodology, utilizing a 90° shift angle to determine water speed and Tip Speed Ratio (TSR) interval. The enhanced dual-stage rotors have successfully attained a Coefficient of Power (Cp), rendering them appropriate for utilization in urban water sources such as sewage pipelines [32]. Prabowoputra & Prabowo extended their work to the Savonius turbine, a widely utilized renewable energy resource, which underwent optimization through CFD design utilizing ANSYS Student edition software. The present study examined the impact of Phase-Shift Angle (PSA) on the turbine performance, finding that a PSA of 30° yielded the most favorable results. The study employed factorial design analysis combined with the CFD approach. The study's results indicate that the PSA substantially impacts the rotor performance. Furthermore, the analysis revealed an interaction between the two components: TSR and PSA. This research work makes a valuable contribution to the advancement of wind energy installations [33]. The research conducted by Edirisinghe *et al.,* on Archimedes Screw Turbines (AST) represents a sustainable technology for extracting energy from mini hydropower sources. The authors employed CFD in examining the efficiency of the turbine, revealing the potential for 80% efficiency in practical implementations [34].

The turbine's efficiency is enhanced through the utilization of the Francis turbine runner in PHES, allowing for efficient flow management and hydraulic efficiency comparable to typical PHES systems [35]. In 2022, Edirisinghe *et al.,* pointed out the study of CFD analysis to optimize the efficiency of a Gravitational Water Vortex Power (GWVP) turbine setup in a conical basin structure [36]. According to Zhou *et al.,* the structural integrity of a floating offshore wind turbine was analyzed through CFD analysis, unveiling the impacts of turbulent wind conditions. The study revealed variations in rotor thrust, power outputs, wake diffusion, and reduced local minimum thrust/power during turbine blade passage [37]. This study simulated load rejection scenarios in pumped storage hydropower plants utilizing CFD and a 1-D, 3-D coupling approach, allowing for efficient allocation of dynamic pressures and flow rates to additional pump turbines [38].

ANSYS Fluent software is widely used for CFD modeling of VAHTs, providing advanced turbulence models for simulating complex flow patterns and analyzing blade design and array configuration effects on turbine performance. Research finding by Benavides-Morán *et al.,* point towards ANSYS-

Fluent, a commercial CFD package, utilizes the Volume Of Fluid (VOF) model to track air-water interface, revealing decreased power and thrust coefficients with closer rotor immersions [39]. Furthermore, Rodríguez *et al.,* showed that ANSYS-Fluent software, which is a commercially available CFD tool, use VOF model to accurately monitor the interface between air and water. Additionally, the unstable Reynolds-averaged Navier-Stokes (URANS) SST k-ω and Transition SST turbulence models are utilised to calculate the unsteady flow field [40]. Rubio-Clemente *et al.,* also provided that the numerical simulation accuracy was improved by utilizing ANSYS Fluent software, which incorporated a 6-DoF user-defined function and URANS equations. This enhanced the performance of the SST k − ω turbulence model [41]. The software ANSYS Fluent was employed to conduct 2D simulations aimed at examining the influence of geometrical parameters on the operating coefficient of H-Darrieus were carried out by Cardona-Cárdenas *et al.,*. The study involved altering the angular velocity and turbulence model, while also calculating the torque [42]. By using CFD in ANSYS Fluent, Borkowski *et al.,* analyse the efficiency of a small hydroelectric power plant at different velocities. It highlights the importance of considering mechanical power losses in the hydro-set gap while assessing performance. The study compares the k-ε and k-ω SST models with the Spalart-Allmaras model, and concludes that the Spalart-Allmaras model is the most suitable. compatible [43]. In a different study, Siswantara *et al.,* applied ANSYS Fluent to assess turbulence models for numerical simulation in a Pico hydro cross-flow turbine. The models were compared using six turbulence models: standard wall function k-ε, scalable wall function k-ε, standard wall function RNG, scalable wall function RNG, standard transitional SST, and transitional SST with curvature corrections. The RNG model with scalable wall function was found to be most accurate [44].

OpenFOAM, a widely-used open-source CFD software, is highly regarded for its versatility and ability to be tailored to specific requirements. This makes it an ideal choice for simulating the distinctive dynamics of VAHTs. Recently, Zhao *et al.,* research presents a computational model of a vertical-axis turbine with active-pitch torque control. The model utilises OpenFOAM to solve URANS equations and analyse the properties of the near-wake [45]. Whereas Samal *et al.,* approach numerical model created in OpenFOAM to consider the impact of surface roughness. This model includes adjustments to the wall function and establishes a correlation for the dimensionless distance between near-wall cell centres [46]. In 2021 Kumar *et al.,* carried out simulation of particles in a highly anisotropic turbulent flow field of a hydrocyclone is carried out using the OpenFOAM 4.1 library, employing a combined Multi-Phase Particle In Cell method (MPPIC) and VOF flow solver [47]. El Fajri *et al.,* noted that OpenFOAM, an open-source flow solver, enhances the accuracy of thrust, power, and intermediate wake predictions for hydrokinetic turbines, primarily due to improved turbulence predictions [48]. As analyzed by Shojaeefard *et al.,* the interaction between the rotor and stator, as well as the losses, in a three-dimensional fluid field of Agnew. The investigation is conducted using OpenFOAM, a computational fluid dynamics model [23].

The STAR-CCM+ programme is renowned for its strong meshing capabilities and extensive physics models. Several conducted studies have utilised STAR-CCM+ software to examine the influence of several environmental factors, such as the relationship between waves and currents, on the effectiveness of VAHTs. Kumari *et al.,* emphasized the need of using the commercially available programmed STAR-CCM+ for evaluating the hydrodynamic characteristics of hydrofoil systems. It allows for the assessment of lift, drag, pressure coefficient, and velocity contour in order to optimise the design of marine propulsion systems for maximum efficiency [49]. While Franck *et al.,* used computational simulation to investigate the hydraulic and sedimentological impacts of the navigation of sizable commercial vessels on the Paraná River. The work employs the Adapco STAR CCM + CFD software to analyse ship navigation in tranquil waters, quantifying wave heights and corroborating findings through experimental models [50]. The approach used by Wu *et al.,* employs CFD to model a 5 MW floating offshore wind turbine. The simulation utilises the STAR-CCM+ programme and solves the Reynolds-averaged Navier-Stokes (RANS) equations along with the re-normalization group (RNG) k-ε turbulence model equations. This work serves as a benchmark for future investigations in the field of coupled aero-hydro simulation were carried out by Wu *et al.,* [51]. Kumari & Chakraborty, suggest the Navier-Stokes equations were solved using STAR-CCM+, which used the k-ε turbulence model to accurately simulate the mechanics of turbulent flow. As highlighted by Kumari & Chakraborty the impact of spacing distance on the lift and drag coefficient in both tandem and staggered arrangements, which are important design factors for tidal turbine blades [52].

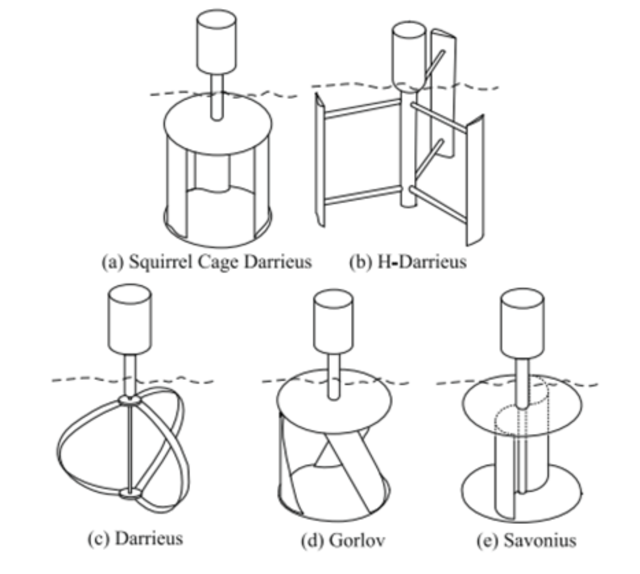

Fig. 1. Vertical axis turbine [53]

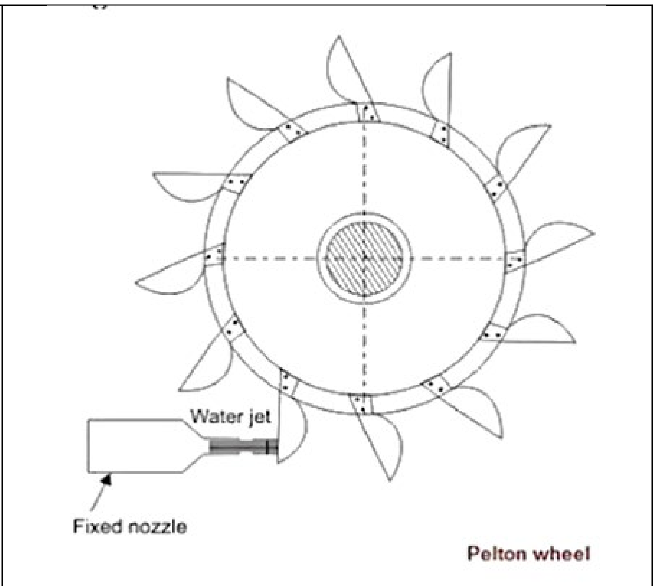

Fig. 2. Pelton wheel outline [54]

3. Methodology

Subsequently, this section undertakes a comprehensive examination and integration of scholarly material to identify, select, and evaluate noteworthy applications of CFD in the VAHKTs context. Finally, our objective was to propose further avenues for research in light of the aforementioned issues outlined in this article. This investigation employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [55], known as a well-recognized and acknowledged standard for carrying out systematic literature reviews. The establishment of publication guidelines aimed to assist authors in evaluating the precision of a critique by providing essential and mandatory details. The guidelines issued by PRISMA also highlight the importance of incorporating randomized evaluations in systematic analysis reports for numerous kinds of research.

3.1 Identification

The process of choosing articles with regard to this research involves three crucial steps within the systematic review methodology. In the initial stage, keywords, concepts related to the research, and related terms are identified by consulting encyclopedias, thesaurus dictionaries, and previously conducted scholarly research. Subsequently, once the pertinent keywords were determined, search strings were formulated for the Web of Science (WoS) as well as Scopus databases, as portrayed in Figure 3. In the initial systematic review process stage, the current research endeavour effectively obtained a total of 315 papers across databases.

Table 1
The search string

Scopus	TITLE-ABS-KEY (("Computational Fluid Dynamic" OR cfd OR "Computational" OR "numerical" OR "simulation") AND ("Hydrokinetic" OR "HYDRO" OR "HKT" OR "HYDRO-KINETIC") AND ("VERTICAL AXIS" OR "VAHT")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO(PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2023)) Access Date: 16 Sep. 23
WoS	("Computational Fluid Dynamic" OR cfd OR "Computational" OR "numerical" OR "simulation") AND ("Hydrokinetic" OR "HYDRO" OR "HKT" OR "HYDRO-KINETIC") AND ("VERTICAL AXIS" OR "VAHT") (Topic) and 2023 or 2022 or 2021 (Publication Years) and English (Languages) and Article (Document Types) Access Date: 16 Sep. 23

3.2 Screening

During the initial phase of screening, identical papers were eliminated. Meanwhile, in the study's preliminary stage, a cumulative count of 220 publications was deemed ineligible for inclusion. Subsequently, in the second phase, a subset of 36 papers were chosen for further assessment, employing the researchers' predetermined criteria for inclusion and exclusion. The main factor considered was the incorporation of scholarly literature, specifically research articles, as a prominent means of obtaining practical guidance. Moreover, this resource encompasses an extensive collection of academic content, including reviews, chapters, books, book series, meta-syntheses, meta-analyses, systematic reviews, as well as conference proceedings, which were not included in the latest academic investigation. Moreover, it is important to acknowledge that the review's scope was limited exclusively to literature composed in the English language. It is crucial to recognize that the plan mentioned above was developed for the previous three-year span covering 2021 to 2023. A total of 22 publications were excluded from the analysis because they did not meet specific criteria.

3.3 Eligibility

The third-level classification, known as "eligibility," encompasses a comprehensive collection of 59 articles. During this phase, a thorough examination was conducted of the titles of all articles and significant text to verify the fulfilment of the inclusion criteria and the suitability of the articles considering the research objectives of the present study. Consequently, 22 papers were removed from the investigation because they lacked relevance between their title and abstract and the research purpose, as determined through empirical data analysis. A total of 37 articles have been made accessible for review, as outlined in Tables 3, 4 as well as 5.

Table 2
The selection criterion searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2021 – 2023	< 2021
Literature type	Journal (Article)	Review, Book, Conference
Publication Stage	Final	In Press

3.4 Data Abstraction and Analysis

In this research, an integrative analysis was employed as the chosen methodological approach to determine as well as integrate various research methods. Scholarly investigation focused on the identification and formulation of suitable subjects and subcategories. The authors conducted a thorough analysis of 37 publications, examining assertions and information pertinent to the subjects addressed in the current study, as illustrated in Figure 3. The initial stage in the progression of the topic involved gathering data. The authors proceeded to summarize each established subject, encompassing any related performance, numerical, and design. In this research, the primary author worked in cooperation with fellow authors to establish as well as construct thematic categories based on the findings. During the data analysis phase, a careful record was consistently kept to record all pertinent analyses, viewpoints, uncertainties, and other considerations that held importance in understanding the data.

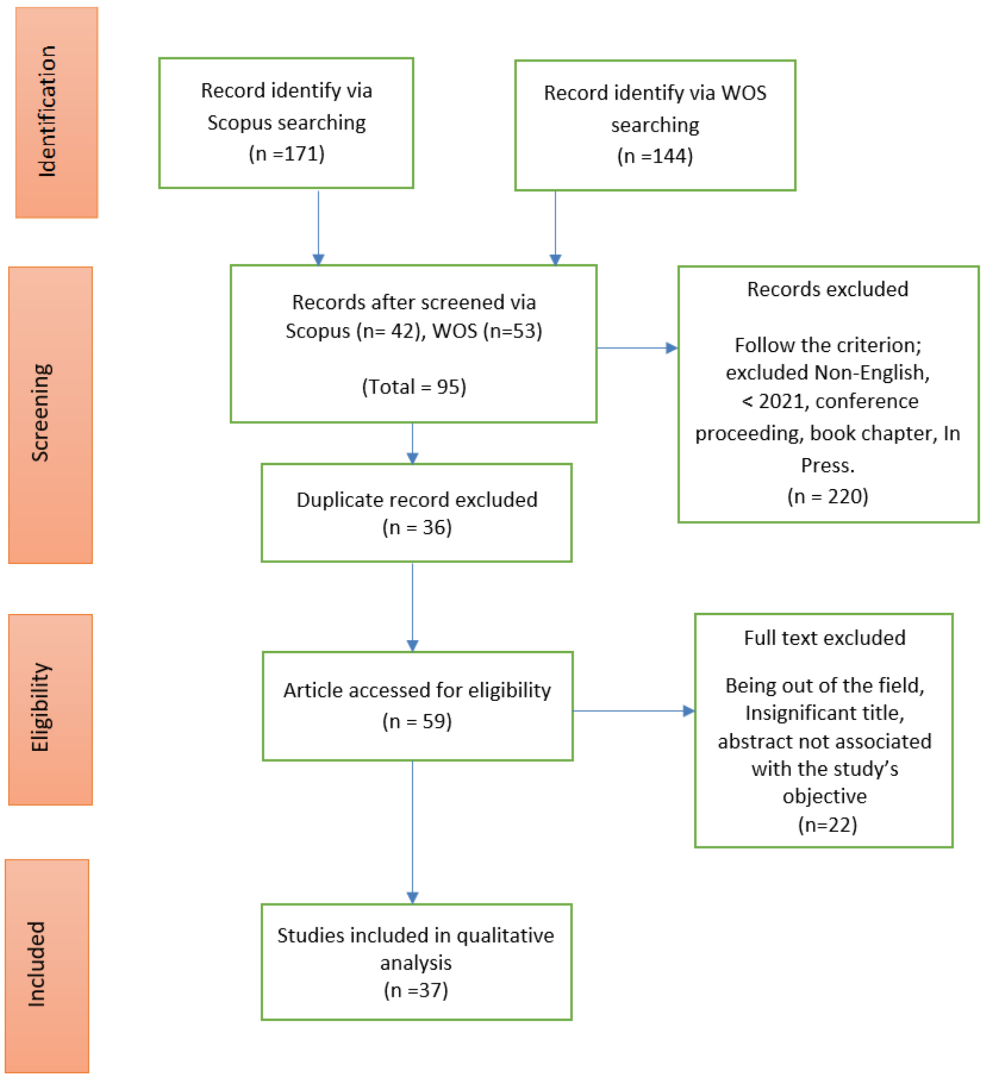

Fig. 3. Proposed searching study flow diagram [55]

The authors additionally compared the results to address any inconsistencies that may potentially arise during the theme development process. It is crucial to acknowledge that when discrepancies arise regarding the themes, the authors actively participate in dialogues to rectify them. Ultimately, the established themes were modified to ensure their logical consistency and homogeneity. To establish the credibility of the assessments, the examinations were conducted by two professionals (Dr. Shamsul Sarip – an expert in CFD) and (Dr. Sa'ardin Abdul Aziz – an expert in Finite Element Modelling). The inclusion of the expert review process has a crucial part in providing the significance, clarity, and adequacy of each sub-theme by confirming domain validity. Modifications have been implemented at the author's discretion, taking into account feedback and opinions provided by specialists.

4. Findings

In this part, the authors present the outcomes and discoveries of the systematic review., focusing on the broad landscape with regard to CFD modelling and simulation techniques applied to VAHKTs. Our investigation has traversed a comprehensive array of research studies, encompassing various facets of VAHT performance, numerical methods, and design parameters. The significance of VAHTs in harnessing the kinetic energy of water currents and generating renewable energy has garnered growing attention in recent years. Understanding the intricacies of their hydrodynamic behaviour is pivotal for optimizing their performance and contributing to sustainable energy solutions. Through our systematic analysis, researchers strive to make valuable contributions to the growing body of knowledge. This ensures future research endeavours toward more efficient and sustainable hydrokinetic turbine systems.

4.1 Performance

Table 3
Synopsis of performance

Authors	Title	Year	Methodology	Results
Gorle J.M.R.; Chatellier L.; Pons F.; Ba M. [56]	Sensitivity analysis of the performance of a Darrieus hydrokinetic turbine in uncertain operating conditions	2021	Response surface analysis, probability density function analysis, and cumulative distribution function analysis are only some of the probability-based methods utilized to assess the turbine's performance's sensitivity to input uncertainty.	The study reveals that uncertainties in the turbine's rotation have a greater impact on power output than variations in free-stream velocity.
Chen D.; Ma Y.; Hu C.; Zhao T. [57]	Efficiency optimization of twin vertical-axis helical hydrokinetic turbines (VAHHTs) based on Taguchi method	2023	The Taguchi method is employed in optimizing the performance of a unique dual vertical-axis helical hydrokinetic turbine.	Results suggest that variables λ, β, RD, φ, and L/D considerably influence the efficacy with regards to twin vertical axis horizontal helical turbines.
Ramadan A.; Hemida M.; Abdel-Fadeel W.A.; Aissa W.A.; Mohamed M.H. [58]	Comprehensive experimental and numerical assessment of a drag turbine for river hydrokinetic energy conversion	2021	The numerical investigation focuses on optimizing the rotor performance by incorporating two shielding plates to achieve additional improvements.	The study's findings present that a rotor with increased fullness demonstrates enhanced operational attributes, as evidenced by a 0.1285 Cp as well as a 0.61 TSR.
Jayaram V.; Bavanish B. [59]	The Influence of the Index of Revolution on	2022	A total of nine turbine models, each having a height as well as a	The simulation results show that the turbine with a revolution index of 0.25 is the

	the Performance of Gorlov Helical Turbine		diameter of 0.6 m, were specifically built to possess varying indexes of revolution. Subsequently, these models were submitted to computer modeling.	most efficient among the classes.
C M S.; Honnasiddaiah R.; Hindasageri V.; Madav V. [60]	The application of vertical axis hydro turbine for sustainable power generation in irrigation channels with different bed slopes	2021	The Savonius rotor, a key component in the Savonius system, has been extensively tested for its performance in various experimental settings.	The power as well as torque coefficients increased to 40% and 10% at a 0.92 TSR as well as 0.5° channel inclination.
Gauvin-Tremblay O.; Dumas G. [61]	Hydrokinetic turbine array analysis and optimization integrating blockage effects and turbine-wake interactions	2022	The recently suggested Effective Performance Turbine Model (EPTM) serves as an appropriate tool for this objective, enabling the examination and evaluation of numerous configurations while maintaining a reasonable computational expense.	The results indicate that staggered Vertical-Axis Turbines (VATs) do not offer any significant advantage and should be favored in their alignment.
Thanatwutthikorn K.; Suntivarakorn R. [62]	Optimal Design of Guide Vane for Improving Mini Hydro Power Plant Efficiency by using Twin Axis Vertical Turbine	2022	A guide vane system was installed for inlet water control, and a CFD simulation was conducted to validate the system, utilizing 5-30 degree inlet angles and 15-40 blade turbines.	The findings suggest that the system reached its highest level of efficiency at 48% when operating with a system head of 0.7 m as well as a 0.4 m^3/s flow rate.
Guevara-Munoz A.; Hincapie-Zuluaga D.; Rio J.S.-D.; Rodriguez-Cabal M.A.; Torres-Lopez E. [63]	Numerical Comparison and Efficiency Analysis of Three Vertical Axis Turbine Of H-Darrieus Type	2023	The turbine design was conducted using ANSYS® Fluent 2022R2 software, utilizing two-dimensional simulations to analyze the turbine under constant operating conditions.	The H-Darrieus turbine, featuring a 1.0 solidity, offers a broader operational spectrum and reduced power as well as torque coefficients.
Zhang A.; Liu S.; Ma Y.; Hu C.; Li Z. [64]	Field tests on model efficiency of twin vertical axis helical hydrokinetic turbines	2022	It explored how rotational direction, spacing, input direction as well as phase difference affect twin vertical axis helical hydrokinetic turbines VAHHT efficiency.	The findings indicate that the torque measurement platform effectively measures water velocity (V), torque (T), as well as rotational speed (ω) concurrently.
C M S.; Madav V. [65]	Numerical and experimental investigation of modified V-shaped turbine blades for hydrokinetic energy generation	2021	Numerical analysis determines the optimal V-angle for an inflow velocity of 0.3090 m/s and a water depth of 70 mm.	The rotor blade's performance with a 1.75 aspect ratio and one middle plate was substantially improved by 86.13% at a TSR of 0.86.
Botero N.; Ratkovich N.; Lain S.; Lopez Mejia O.D. [66]	Synthetic jets as a flow control device for performance enhancement of vertical	2022	The Unsteady Reynolds Averaged Navier-Stokes (URANS) equations were solved utilizing the k-ω SST	Utilizing tangential synthetic jets on both the outer as well as inner surfaces of an airfoil leads to a significant boost in

	axis hydrokinetic turbines: A 3D computational study		turbulence model in the Star CCM+ software.	the turbine's torque and power generation.
Mohamed O.S.; Melani P.F.; Balduzzi F.; Ferrara G.; Bianchini A. [67]	An insight into the physical mechanisms responsible for power augmentation in a pair of counter-rotating Darrieus turbines	2023	This study investigates the performance of two Darrieus hydrokinetic turbines by analyzing their inward and outward rotation by applying unsteady CFD.	The findings suggest that dual rotors' most efficient operating point for the studied turbines is shifted toward higher TSRs.

4.2 Numerical

Table 4
Synopsis of numerical

Authors	Title	Year	Methodology	Results
Mosbahi M.; Lajnef M.; Derbel M.; Mosbahi B.; Aricò C.; Sinagra M.; Driss Z. [68]	Performance improvement of a drag hydrokinetic turbine	2021	The ANSYS FLUENT 17.0 software was utilized to conduct numerical simulations.	The suggested deflector system's effectiveness in enhancing the Savonius rotor's Cp has been empirically demonstrated, resulting in a notable increase of 14%.
Zhao R.-W.; Creech A.C.W.; Li Y.; Venugopal V.; Borthwick A.G.L. [45]	Numerical analysis of the performance of a three-bladed vertical-axis turbine with active pitch control using a coupled unsteady Reynolds-averaged Navier-Stokes and actuator line model	2023	The URANS model is utilized in a turbine model for predicting Tidal tides, utilizing the Wind and Tidal Turbine Embedded Simulator as well as the actuator line method.	Utilizing a pitch-controlled system has been discovered to significantly influence the operational effectiveness of a VAKHT. This system effectively minimizes turbulence, mitigates the severity of vortex shedding, and reduces the detached vortices' size.
Hantoro R.; Sarwono; Panjaitan F.P.; Septyaningrum E.; Hidayati N. [69]	Site test performance and numerical study of vertical axis hydrokinetic turbine straight blade cascaded (Vaht–sbc)	2021	The present investigation was carried out through the utilization of experimental and numerical analysis techniques.	The relationship between the turbine's speed and torque and the generator's rotational speed is found to be exactly proportionate while being inversely connected with the load, as indicated by the CFD simulation.
Doan M.N.; Obi S. [70]	Numerical study of the dynamic stall effect on a pair of cross-flow hydrokinetic turbines and associated torque enhancement due to flow blockage	2021	The research employed a 2D Reynolds-averaged Navier-Stokes (RANS) simulation model to examine the efficiency of a cross-flow hydrokinetic turbine and a dual turbine system with counter-rotating arrangements.	This study investigated the phenomenon of dynamic stall and its associated Leading Edge Vortex (LEV) formations, exploring their relationship with power generation.
Tigabu M.T.; Khalid M.S.U.; Wood D.; Admasu B.T. [5]	Some effects of turbine inertia on the starting performance of the vertical-axis hydrokinetic turbine	2022	The study uses computational methods to examine the impact of inertia on a turbine's behavior from rest to runaway state during its initial startup.	The addition of mass to a blade significantly affects its dynamics, with the highest overshoot occurring at minimum inertia, varying with blade mass and water speed.

Mejia O.D.L.; Mejia O.E.; Escorcia K.M.; Suarez F.; Laín S. [71]	Comparison of sliding and overset mesh techniques in the simulation of a vertical axis turbine for hydrokinetic applications	2021	The utilization of CFD	The goal of the comparison was to assess the model capabilities, performance parameters, and computational costs of turbine models in order to accurately represent complicated flow phenomena.
C M S.; Honnasiddaiah R.; Hindasageri V.; Madav V. [72]	Experimental and numerical investigation of novel V-shaped rotor for hydropower utilization	2021	V-shaped rotor blade profiles in a tilting water flume were simulated using ANSYS Fluent.	The optimal blade profile (V4) achieved a 0.22 maximum Cp as well as 0.21 at a TSR of 0.87.
Bayram A.; Dhalwala M.; Oshkai P.; Korobenko A. [73]	Numerical simulations of a vertical-axis hydrokinetic turbine with different blade-strut configurations under free-surface effects	2023	The research examined the hydrodynamics of a vertical-axis hydrokinetic turbine by analyzing the flow characteristics of the free surface under different blade-strut combinations.	The study's results indicate that the existence of a turbine wake significantly influences the distortion of the air-water interface.
Kang C.; Wang Z.; Kim H.-B.; Shao C. [74]	Effects of solidity on startup performance and flow characteristics of a vertical-axis hydrokinetic rotor with three helical blades	2023	CFD and six degrees of freedom (SDOF) methods are utilized to analyze instantaneous flows and evaluate rotor performance.	The findings indicate that there is a gradual change in the torque coefficient concerning the azimuthal angle, and it reaches a minimum value exceeding 0.08.
Mohamed O.S.; Melani P.F.; Balduzzi F.; Ferrara G.; Bianchini A. [75]	An insight on the key factors influencing the accuracy of the actuator line method for use in vertical-axis turbines: Limitations and open challenges	2022	The interaction between the blade and the flow is represented by incorporating an equivalent momentum loss, which results in the introduction of analogous aerodynamic forces inside the computational domain of the CFD simulation.	The study concludes that the ALM method can generate accurate flow field solutions for high and medium TSR, with current knowledge sufficient for model setting, and a better dynamic stall model could improve ALM accuracy.
Descoteaux P.-O.; Olivier M. [76]	Performances of vertical-axis hydrokinetic turbines with chordwise-flexible blades	2021	The simulations utilized a partitioned Fluid-Structure Interaction (FSI) code in OpenFOAM for numerical analysis.	The research indicates that there is a 12% to 15% increase in efficiency when moderate flexibilities are applied at a TSR of 2 (below the optimal value) as well as 6 (above the optimal value).
Melani P.F.; Balduzzi F.; Ferrara G.; Bianchini A. [77]	Development of a desmodromic variable pitch system for hydrokinetic turbines	2021	The numerical approaches used in the ANSYS® WORKBENCH® 20.2 suite are analyzed using various numerical methods.	Variable pitch offers a promising solution for VAKHT, enhancing efficiency by 35% and reducing machine unsteady loads.
Dorge C.; Bibeau E.L. [78]	Deep Learning-Based Prediction of Unsteady Reynolds-Averaged Navier-Stokes Solutions for Vertical-Axis Turbines	2023	The Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations were conducted at various free-stream velocities, enhancing the performance of the	Angular velocity predictions, as well as turbulent viscosity, were improved by reducing data dimensions and raising training cases, resulting in reduced relative error.

			Convolutional Neural Network.	
Devin M.C.; Mendoza N.R.; Platt A.; Moore K.; Jonkman J.; Ennis B.L. [79]	Enabling Floating Offshore VAWT Design by Coupling OWENS and OpenFAST	2023	The integration of the Offshore Wind Energy Simulator (OWENS) with many OpenFAST modules has been undertaken to enhance the modeling capabilities of floating offshore wind turbines.	The verification test conducted on OWENS and the subsequent analysis of OpenFAST simulation results has provided empirical evidence to support OWENS's enhanced modeling and simulation capabilities specifically tailored for floating Vertical Axis Wind Turbine (VAWT) applications.

4.3 Design Parameter

Table 5
Synopsis of design parameter

Authors	Title	Year	Methodology	Results
Duarte L.; Maguin N.; Dellinger G.; Dellinger N.; Vazquez J. [80]	Numerical investigation of a two-bladed vertical-axis turbine operating in a confined channel	2022	Unsteady RANS equations are accurately reproduced using a 2D numerical model in OpenFOAM, which employs a finite volume approach for accurate simulation.	The study suggests that the optimal ε0 setting is crucial for optimal energy harvesting. By setting a threshold value of ε0 greater than 9, you ensure that the turbine's performance aligns with the performance of an unrestricted turbine.
Hu Z.; Wang D.; Lu W.; Chen J.; Zhang Y. [81]	Performance of vertical axis water turbine with eye-shaped baffle for pico hydropower	2022	The velocity of water is a critical factor with regard to the design and operation of water distribution systems, particularly in confined spaces.	The investigation findings indicate that the utilization of a water baffle opening of 30mm and a rotor angle of 52° resulted in the attainment of the highest efficiency, which was measured at 5.93%.
Yosry A.G.; Álvarez E.Á.; Valdés R.E.; Pandal A.; Marigorta E.B. [82]	Experimental and multiphase modeling of small vertical-axis hydrokinetic turbine with free-surface variations	2023	A prototype of a vertical-axis turbine has been created and constructed for experimental purposes experimental evaluation in an unobstructed water channel.	The velocity is found to increase the peak Cps.
Gao J.; Liu H.; Lee J.; Zheng Y.; Guala M.; Shen L. [83]	Large-eddy simulation and Co-Design strategy for a drag-type vertical axis hydrokinetic turbine in open channel flows	2022	In this study, authors employed high-fidelity large-eddy simulations (LES) to assess a turbine's operational efficiency and examine its wake's properties. This study aims to enhance the turbine's design by taking into account various operational situations and blade configurations.	The co-design technique employed in this study aims to improve blade geometry through a series of iterative processes. The main goals of these iterative processes are to reduce shear stress along the stream bank and optimize the Cp to its maximum potential. These two metrics are considered in combination to evaluate the effectiveness of the enhancements made.

Ma Y.; Zhu Y.; Zhang A.; Hu C.; Liu S.; Li Z. [84]	Hydrodynamic performance of vertical axis hydrokinetic turbine based on Taguchi method	2022	The Taguchi method optimized the standard parameters associated with a vertical-axis turbine.	The optimized turbine's Cp is 0.1951, a significant increase from the preliminary design, and exhibits a significant reduction of 87.56% in Cp fluctuation.
Villeneuve T.; Dumas G. [85]	Impact of some design considerations on the wake recovery of vertical-axis turbines	2021	The study analyzes and compares the wake dynamics of a single-blade turbine at two different blade attachment points and designs of blade support structures.	The study's results demonstrate that the placement of the blade attachment point along the chordwise direction has a notable effect on the temporal progression of blade circulation via a single revolution of the turbine.
Talukdar P.K.; Kulkarni V.; Chatterjee D.; Saha U.K. [86]	Vertical-axis hybrid turbines as wind and hydrokinetic energy harvesters: technological growth and future design strategies	2023	The design criteria that determine the configuration of a hybrid turbine include overlap ratio, rotor position, solidity ratio, blade form, radius ratio as well as attachment angle.	Results indicate that the maximum Cp values fall within the range of 0.08 to 0.51.
Bizhanpour A.; Hasanzadeh N.; Najafi A.F.; Magagnato F. [87]	Investigation of different deflector geometry and mechanism effects on the performance of an in-pipe hydro Savonius turbine	2023	Five different types of deflector geometry were numerically examined for varying flow rates in an in-pipe Savonius turbine.	A deflector with a moving guide vane, capable of dynamically adjusting position at different flow rates, demonstrated significantly better performance compared to the optimal design point.
Sheikh S.R.; Shah S.H.R.; Rauf U.; Rauf F.; Kausar Z.; Aziz U.; Shah M.F.; Yaqoob H.; Niazi M.B.K. [88]	A low-cost, sustainable energy solution for pristine mountain areas of developing countries	2021	The proposed solution involves a preliminary hydrodynamic design utilizing Qblade and further analysis through numerical simulations.	The study indicates that microturbines are feasible due to their 2100 kWh/year/m2 power generation density with minimal environmental impact.
Bhagat R.; Kumar D.; Sarkar S. [89]	Employability of vertical axis crossflow whirlybird rotor as hydrokinetic turbine and its performance prediction corresponding to different design parameters	2021	The CFD numerical approach is utilized to calculate torque, power, Cp, as well as torque coefficient at various angular speeds and TSRs.	The Cp as well as maximum torque, possess an initial rise as a function of blade number, angle, and length, followed by a subsequent significant drop.
Khan Z.U.; Ali Z.; Uddin E. [90]	Performance enhancement of vertical axis hydrokinetic turbine using novel blade profile	2022	Unsteady RANS CFD simulations were conducted to evaluate and compare the performance with regard to the proposed blade profile relying on an S1048 airfoil.	The utilization of a novel blade profile may enhance the maximum Cp of a traditional design by 14% when operating at a TSR of 1.

5. Conclusions

From a performance perspective, this study holds significant implications. Firstly, it suggests that the findings can potentially drive the widespread adoption of hydrokinetic turbines in river environments, which could revolutionize renewable energy production. Furthermore, the study delves into rotor optimization, numerically investigating the effects of adding shielding plates to enhance performance. The results highlight the correlation between rotor fullness and improved operating characteristics, particularly concerning the Cp, emphasizing the significance of design factors. Additionally, the study sheds light on a critical aspect of turbine performance, emphasizing that the precision of turbine rotation plays a more substantial role in power output than free-stream velocity. Lastly, the research provides practical guidelines for turbine placement within an array, emphasizing inward rotation and offering insights into lateral as well as longitudinal spacing. Integrating a novel parameter in assessing the increasing power contribution of additional rows of turbines enhances the comprehension of the dynamics of turbine arrays. In conclusion, this study offers a comprehensive performance perspective on hydrokinetic turbines, with valuable insights for optimizing their efficiency and practical deployment.

The implementation of a novel system exhibits potential from a quantitative standpoint. This development is expected to result in enhanced river and channel flow exploitation to generate power in rural regions. Integrating a pitch-controlled system signifies a noteworthy theoretical progression in turbine technology. The demonstration highlights the potential for enhanced efficiency of hydrokinetic turbines through the reduction of turbulence generated during turbine rotations, mitigation of vortex shedding, and optimization of performance for rated tip-speed ratios. The study results also provide significant insights into turbine design, namely in optimizing overshoot minimization and reducing starting time. Furthermore, the thorough evaluation of performance prediction and computational skills across several models displays a dedication to rigor in the research. The findings highlight the resilience of the numerical formulation and present opportunities for further investigation, underlining the study's importance in furthering the fields of renewable energy technology and CFDs.

ANSYS Fluent is a popular CFD software for VAHT, renowned for its advanced turbulence models and ability to simulate complex flow patterns. It effectively analyzes blade design and array configurations, focusing on rotor immersion effects and numerical simulation accuracy. However, OpenFOAM, a widely recognized open-source software, is highly regarded for its precise prediction of turbulence in three-dimensional fluid fields, making it exceptionally versatile in analyzing unique VAHT dynamics. In contrast, STAR-CCM+ is a highly effective tool for enhancing turbine blade designs, providing strong meshing capabilities and extensive physics models for evaluating hydrodynamics and assessing the environment. Overall, the current scenario of CFD modelling and simulation in VAHT is characterised by the use of advanced software tools such as ANSYS Fluent, OpenFOAM, and STAR-CCM+. These technologies provide a variety of functions, including thorough modelling of turbulence and study of specific environmental factors. These capabilities are essential for optimizing turbine performance and improving efficiency in hydrokinetic energy generation.

The study introduces a framework that exhibits a wide range of potential applications in water-based settings, emphasizing its capacity to adjust to diverse circumstances and energy requirements. By employing a process of iterative design refinement, this study incorporates lower shear stress and improved Cp into the blade shape. This approach holds promise for extracting renewable energy while yielding favourable environmental outcomes. Moreover, this study offers valuable insights into the design of vertical axis turbines that maximize efficiency and highlights the crucial influence of geometric factors on the distribution of vorticity and the recovery of the wake. This indicates that even little alterations can significantly influence the efficiency of the turbine. In conclusion, the study comprehensively analyzes potential future methods for developing hybrid turbine designs. The research emphasizes the importance of adopting an interdisciplinary approach to optimize efficiency and promote sustainability in renewable energy systems.

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