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Review

Improved Hydrodynamics and CFD-FEM Integration for High-Performance Annular Reactors: A Comprehensive Review

Krishanu Roy[1], Sabyasachi Paitandi[2], Sankha Chakrabortty[3,*]

[1]Department of Mechanical Engineering, Dr. Bidhan Chandra Roy Engineering College, Durgapur, India

[2]Department of Electrical Engineering, Birbhum Institute of Engineering and Technology, Suri, India

[3]School of Chemical Engineering, KIIT Deemed to be University, Bhubaneswar, India

[*]Corresponding author: Sankha Chakrabortty, sankha.chakrabortty@kiitbiotech.ac.in

Abstract

Enhanced hydrodynamics has emerged as a powerful strategy for improving mixing, Residence Time Distribution (RTD), and coupled mass-heat transfer within annular reactors, offering substantial benefits for both plug-flow and continuous operation modes. By promoting superior flow distribution and turbulence control, hydrodynamic intensification enables higher reaction efficiencies, improved scalability, and greater energy economy—attributes that increasingly position annular reactors as attractive platforms for chemical, environmental, and energy-related processes. Over the past decade, significant progress has been made in understanding the fundamental hydrodynamic behaviour of annular configurations, driven largely by advances in high-fidelity numerical tools. This review synthesizes current developments in the field, with emphasis on the role of Computational Fluid Dynamics (CFD) and coupled CFD-Finite Element Method (CFD-FEM) frameworks in evaluating flow regimes, transport mechanisms, and reactor-structure interactions. By critically examining recent modelling approaches, design innovations, and performance metrics, the review highlights how computational insights are supporting the evolution of compact, high-efficiency, and energy-optimized annular reactor technologies. The article also identifies key challenges, methodological limitations, and future opportunities for integrating advanced simulations with experimental validation to accelerate the adoption of annular reactors in next-generation process systems.

Keywords

Annular reactor, CFD, FEM, Laminar flow, Enhanced hydrodynamics, Simulation, Structural analysis

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1. Introduction

Annular reactors have gained increasing importance in chemical, biochemical, and environmental process engineering due to their distinctive ability to regulate fluid dynamics, promote efficient mixing, and enhance both mass and heat transfer. Their concentric cylindrical configuration creates a narrow annular gap between the inner and outer walls, enabling precise manipulation of hydrodynamic conditions. The compact architecture and high surface-to-volume ratio of these systems make them particularly advantageous for continuous-flow and plug-flow operations, where improved Residence-Time Distribution (RTD), uniform reactant exposure, and controlled shear are essential for optimizing reaction kinetics and product selectivity [1,2].

Compared with conventional tubular or packed-bed systems, annular reactors have been reported to improve process efficiency substantially—reducing energy consumption by 15-25% and equipment size by 30-40%. These benefits translate into lower utilities, decreased capital expenditure, and enhanced scalability, making annular designs attractive for industrial applications ranging from photocatalysis and wastewater treatment to fermentation, advanced oxidation, and hydrogen-storage processes. Their ability to maintain predictable velocity profiles and consistent mixing behaviour further minimizes dead zones and axial dispersion, issues frequently encountered in traditional reactor geometries. Such stable hydrodynamic performance is especially valuable for exothermic, shear-sensitive, or laminar plug-flow processes.

The growing demand for compact, high-throughput process technologies has accelerated the adoption of annular reactors in both laboratory and industrial settings. In systems where fluid motion strongly influences performance, Computational Fluid Dynamics (CFD) serves as a powerful tool for analysing hydrodynamics. By solving the governing fluid-flow equations, CFD provides high-resolution insights into velocity distributions, pressure gradients, shear stresses, thermal profiles, and flow structures within complex geometries [3]. These simulations allow engineers to detect stagnation regions, assess heat- and mass-transfer behaviour, and optimize flow paths—often without the need for extensive prototyping—making CFD invaluable for contemporary reactor design and performance improvement [4-6].

The geometry of annular reactors introduces key design parameters, such as the Length-to-Diameter ratio and annular gap width (δ), that strongly influence hydrodynamic behaviour. Narrower gaps promote steeper axial velocity gradients and improved heat transfer but at the expense of higher pressure drop. Such design trade-offs become critical during transitions between laminar, transitional, and turbulent flow regimes. In general, flow behaviour is governed by the Reynolds number (Re), where $Re \leq 2300$ corresponds to laminar flow, $Re \geq 4000$ to turbulence, and intermediate values to transitional flow. At a calculated Reynolds number of approximately 164.2, annular reactor systems typically operate in a laminar regime under standard conditions [7,8]. Laminar flow is characterized by orderly streamlines, low mixing in the radial direction, and highly controlled residence-time behaviour—factors beneficial for sensitive reactions such as biofilm formation, thin-film deposition, and enzyme or catalyst mediated processes [9]. Analytical solutions for annular laminar flow, as demonstrated by Shah and London [7] and Kakac et al. [8], provide a valuable foundation for validating CFD simulations and informing subsequent structural analyses using the Finite Element Method (FEM). The narrow radial gap of annular reactors also enables efficient thermal management for heat-sensitive or rapid reactions. Localized heating or cooling jackets can maintain uniform temperature profiles even during transient operation. Furthermore, annular geometries are well suited to modular "number-up" scale-up strategies commonly used in microreactor systems, offering reproducible performance across multiple units. Advances in digital design tools have further accelerated progress, with CFD and FEM now employed together to analyse hydrodynamics, thermal stresses, structural deflections, fatigue behaviour, and creep during reactor operation. This integrated hydrodynamic-mechanical assessment is crucial when designing reactors for high-temperature or mechanically demanding conditions [3,6]. Recent research has also focused on strategies to improve turbulence characteristics, mixing intensity, and heat-transfer efficiency through engineered surface modifications, such as helically coiled inserts, textured walls, or controlled surface roughness. While enhanced turbulence can significantly accelerate reaction rates, it may also introduce higher mechanical loads on reactor walls, thereby necessitating coupled hydrodynamic-mechanical simulations to ensure structural reliability [10,11]. With ongoing developments in smart sensors, digital control systems, and advanced materials, annular reactors are increasingly viewed as next-generation platforms capable of overcoming long-standing limitations in traditional reactor technologies.

This review provides a comprehensive evaluation of annular reactor hydrodynamics and mechanical design considerations. Emphasis is placed on simulation-guided design strategies based on CFD and FEM, along with insights into material selection, reactor durability, and optimization of laminar-flow configurations. The overarching goal is to demonstrate how simulation-assisted methodologies can lead to compact, efficient, stable, and scalable annular reactor systems suitable for modern industrial and laboratory applications. Through the combined use of computational modelling (CFD under FEM) and analytical frameworks [12], the field is moving toward intelligent, high-performance reactor platforms capable of addressing future challenges in process engineering.

2. Methodology of This Review

The methodology adopted in this review was designed to establish a clear, transparent, and reproducible protocol for identifying, screening, and synthesizing research related to annular reactor design, hydrodynamics, and multi-physics simulation approaches. The process consisted of three sequential stages: literature identification, eligibility assessment, and structured synthesis. In the first stage, relevant publications were collected from major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Keyword combinations such as “annular reactor”, “hydrodynamic modeling”, “CFD-FEM coupling”, “laminar annular flow”, “reactor structural analysis” and “Fluid-Structure Interaction (FSI)” were used to ensure comprehensive coverage. The search was restricted to peer-reviewed articles, conference proceedings, and authoritative reports written in English and published within an appropriate timeframe to capture both classical studies and recent methodological advances.

In the second stage, a two-step eligibility screening was performed. Titles and abstracts were initially examined to determine thematic relevance. Papers unrelated to annular geometries, multi-physics modeling, or reactor-scale transport phenomena were excluded. Full-text evaluation followed, assessing whether the study presented (i) clearly described experimental or computational methods, (ii) quantifiable results relevant to hydrodynamic or structural behavior, and (iii) technical details sufficient for comparison across studies. Publications with unclear methodology, insufficient data, or unverifiable claims were removed to maintain scientific reliability.

The final stage involved organizing the selected literature into coherent analytical categories. Studies were grouped according to their primary contribution—hydrodynamic behavior of annular flows, CFD model development, FEM-based structural assessment, FSI frameworks, geometric optimization strategies, and performance enhancement through internal structures or surface engineering. This categorization enabled consistent comparison of modeling assumptions, boundary conditions, meshing approaches, solver settings, and validation techniques across different works. Particular attention was given to identifying how CFD and FEM were integrated, the computational requirements reported, and any limitations acknowledged by the authors.

Throughout the synthesis, efforts were made to avoid redundancy, maintain consistent terminology, and present findings in a manner that reflects the diversity of methodological approaches without overstating conclusions. The methodology does not claim to exhaustively cover all published research but instead focuses on technically detailed, methodologically transparent studies that directly inform the understanding of annular reactor hydrodynamics and structural behavior. This structured approach provides a clear foundation for the discussions that follow and ensures that interpretations presented in this review are grounded in systematically evaluated and thematically aligned evidence.

3.Fundamentals of Annular Reactor Hydrodynamics

The hydrodynamic annular reactor has emerged as an important platform in modern chemical, environmental, and energy-related processing due to its ability to provide highly controlled flow environments. Its characteristic cylindrical geometry enables superior manipulation of flow profiles, RTD, and interfacial transport phenomena, making it advantageous compared to conventional reactor designs [13]. The inherently high surface-to-volume ratio of annular configurations also promotes efficient thermal management and allows precise modulation of shear-stress fields, qualities that render these systems particularly attractive for continuous-flow operations [14]. Owing to these structural and operational strengths, annular reactors have been widely explored for heat-sensitive reactions and for processes that benefit from approximate plug-flow behavior [15,16].

Fluid motion within annular geometries can vary considerably, with ordered laminar regimes coexisting alongside more complex or chaotic structures depending on operating conditions [17]. Broadly, fluid flow is classified into laminar, transitional, and turbulent regimes, each exhibiting distinct implications for mass and heat transfer. Laminar flow is characterized by smooth, layered motion with minimal mixing, whereas turbulent flow displays highly irregular velocity fluctuations typical at higher flow rates or Reynolds numbers [18]. Transitional flow represents the intermediate regime where instabilities begin to develop. The foundational work of Osborne Reynolds in the 1880s established the Reynolds number, Re, as the critical dimensionless parameter used to categorize these flow regimes in pipe systems. In the present system, the Reynolds number is approximately 164.2, placing the operation well within the laminar regime ($Re \leq 2300$) [19].

The Reynolds number reflects the balance between inertial and viscous forces in a flow. At low to moderate Re values, viscous forces dominate, suppressing velocity fluctuations and maintaining a stable flow structure [20]. For non-circular geometries such as annular reactors, the hydraulic diameter is used in place of the conventional pipe diameter when evaluating the Reynolds number. In this context, the hydraulic diameter, Dh, is defined as [13]:

$$D_h = D_o - D_i \tag{1}$$

Having well-defined Reynolds number limits for laminar, transitional, and turbulent flow is conceptually desirable, yet in practice these thresholds are influenced by multiple interacting factors rather than a single critical value [21]. The transition from laminar to turbulent flow is governed not only by Reynolds number but also by the magnitude of imposed disturbances arising from surface roughness, geometric imperfections, structural vibrations, and inherent flow instabilities within annular conduits. In general, internal flows in annular pipes exhibit laminar behavior when the Reynolds number remains below approximately 2300; under such conditions, calculated Reynolds numbers typically indicate stable laminar regimes [22,23]. Notably, several studies have demonstrated that in highly polished annular systems operated under carefully controlled conditions with negligible external perturbations, laminar flow can persist at Reynolds numbers approaching 10^5 [24].

The analysis of fluid motion under low-compressibility conditions, such as liquid flow or low-velocity gas flow, is conventionally addressed within the framework of hydrodynamics [25], with hydraulics representing its application to pipeline and open-channel systems [26,27]. This contrasts with gas dynamics, which concerns flows exhibiting significant density variations, typically at high velocities [28]. Across annular reactor configurations reported in the literature, laminar flow is frequently associated with parabolic velocity profiles, limited axial dispersion, and uniform wall shear. These characteristics are widely recognized as advantageous for achieving homogeneous reactant exposure and for processes sensitive to shear, including catalytic reactions, enzymatic transformations, and biofilm-mediated operations.

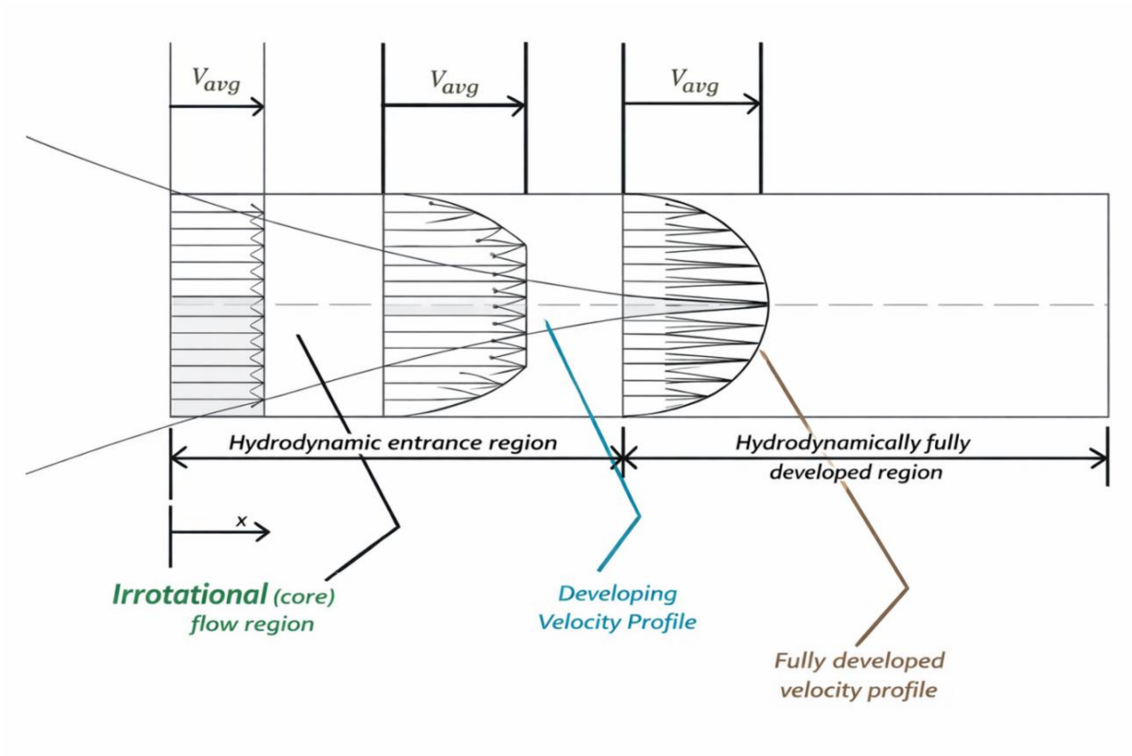

Figure 1. The velocity boundary layer profile formation in a pipe. (The fully developed velocity profile is observed for laminar flow, whose profile is perfectly parabolic(or, near-parabolic); however, for turbulent flow, the profile exhibits a flatter profile due to tremendous momentum exchange across the layers).

Annular reactors are widely recognized in chemical, biochemical, and catalytic engineering as adaptable platforms due to their flexible geometrical configurations and favourable transport characteristics [29]. Rather than being defined by a single configuration, prior studies collectively demonstrate that reactor performance is strongly influenced by general geometric parameters such as annular gap width, axial length, and length-to-diameter ratio, which together govern pressure drop, RTD, and mass-transfer efficiency [30]. Across reported designs, these parameters determine hydrodynamic stability and process scalability rather than any single fixed dimension.

Reactor geometry has been shown to significantly affect RTD, wall shear stress, and velocity uniformity factors that are critical for maintaining process efficiency and selectivity [31]. Literature consistently reports that laminar-flow regimes in annular configurations promote narrow RTDs approaching plug-flow behaviour, which is advantageous for reaction control. Uniform wall shear stress is particularly important in bio-assisted and surface-mediated processes, where shear values below approximately 0.1 Pa are required to sustain biomass adhesion and effective nutrient transport [4]. In addition, annular reactors typically exhibit high surface-to-volume ratios, enhancing heat and mass transfer while allowing rapid thermal response and minimizing the formation of localized hotspots. Low radial thermal resistance, reported for insulating wall materials with conductivities around 0.03 W m^{-1} K^{-1}, further supports precise temperature regulation in exothermic, photochemical, and catalytic systems.

Engineering investigations of annular reactors generally employ analytical, numerical, and experimental methodologies [32]. While analytical approaches offer closed-form solutions under idealized conditions [33], their applicability is limited for complex geometries. Experimental studies provide valuable validation but are resource-intensive and time-consuming [34]. Consequently, numerical techniques such as the FEM, Finite Volume Method (FVM), Finite Difference Method (FDM), and Boundary Element Method (BEM) have become central to contemporary reactor analysis, enabling multi-dimensional (1D-3D) evaluation of transport phenomena under realistic operating conditions [35].

Within this broader methodological landscape, CFD has emerged as a powerful tool for elucidating annular reactor hydrodynamics. CFD studies reported in the literature routinely examine velocity profiles, pressure gradients, thermal fields, and wall shear distributions, while identifying recirculation zones, flow maldistribution, and stagnant regions that can compromise performance [6,17,36]. When integrated with structural simulations, CFD-based FEM analyses further allow assessment of thermal stresses, deformation behaviour, and fatigue susceptibility under cyclic operation [12]. Such coupled modelling approaches have demonstrated notable performance enhancements in diverse applications, including hydrogen storage and catalytic systems, where improvements in transport kinetics and structural reliability have been reported. Material selection is another recurring theme across annular reactor studies. Annealed stainless steels, particularly SS 304 and SS 316, are frequently recommended due to their balanced combination of machinability [10], mechanical robustness [11], corrosion resistance [36], and thermal stability [16]. These attributes, together with favourable lifecycle performance, make stainless steels preferable to coated or plated alternatives in demanding thermal and reactive environments.

Table 1. Comparison of annealed stainless steel and chrome-plated stainless steel for choosing as a material for an annular reactor.

Properties	Annealed Stainless Steel	Chrome-Plated Stainless Steel
Corrosion Resistance	High (as distributed throughout the material thickness)	Moderate (surface-dependent and prone to localized failure if damaged)
Thermal Stability	Excellent (suitable for hightemperature gradients)	Moderate
Mechanical Workability	Excellent (due to annealing); Easy for machining and welding.	Fair
Structural Integrity	High (uniform strength and ductility)	The surface is hard but may crack
Surface Wear Resistance	Moderate	High
Maintenance & Cleaning	Good	Excellent
Cost	Moderate	Higher than annealed steel
Typical Applications	Chemical, thermal, and pressure-bearing reactors	Photocatalytic bioreactors with low thermal stress

Annular reactors have emerged as versatile platforms in modern process engineering owing to their scalability, controllable hydrodynamics, and compatibility with microreactor technologies. Their intrinsic advantages–compact design, low energy demand, and reproducible flow characteristics–make them suitable for diverse applications ranging from pharmaceutical synthesis to advanced oxidation processes [37]. The functional potential of these reactors is further enhanced through appropriate material selection and integration with intelligent, real-time control frameworks, enabling precise modulation of reaction environments. In the present design, Annealed Stainless Steel (SS 304/316) has been selected as the reactor body based on its superior corrosion resistance [36], high thermal stability [16], and mechanical robustness under operational loads [10]. Compared to chrome-plated variants, annealed stainless steel provides improved machinability, structural resilience, and long-term durability, making it an optimal choice for continuous-flow configurations. Geometrically, the reactor is constructed with a hydraulic diameter of 8 mm and an overall length of 1 m, employing an outer diameter of 40 mm and an inner diameter of 32 mm. These dimensions generate a stable laminar regime ($Re \approx 164.2$), supporting predictable shear and pressure distributions that are essential for accurate transport analysis.

Annular reactor configurations are increasingly recognized for their mechanical robustness and favorable hydrodynamic characteristics across a wide range of operating conditions. Owing to their geometry, annular channels inherently resist deformation even under low internal pressures, thereby ensuring dimensional stability during prolonged operation. Recent advances in additive manufacturing have further expanded the design space of annular systems, enabling flexible customization of channel dimensions and architectures. This has facilitated simulation-driven optimization approaches, allowing reactor performance to be tailored systematically rather than relying on fixed geometrical constraints. From a transport perspective, reactor efficiency in annular systems is governed by the coupled effects of geometry, flow regime, and mass-transfer characteristics. In micro- and meso-scale annular reactors, maintaining laminar flow is particularly desirable, as it ensures predictable velocity distributions, minimizes energy losses, and enables accurate control over residence time and transport phenomena. Reynolds numbers well below the turbulent transition are commonly reported in such systems, consistent with observations across the literature on narrow-gap and annular microreactors. Verification of laminar behavior therefore serves as a critical validation step for computational studies, as it reduces uncertainty associated with scale effects and supports reliable interpretation of CFD predictions. Within this broader context, the integration of computational fluid dynamics with structural and thermal analyses provides a powerful framework for annular reactor design. Rather than focusing on a single geometry or operating point, CFD-FEM coupling enables systematic exploration of flow stability, pressure drop trends, and mechanical integrity across a range of configurations. Such an approach strengthens the general applicability of annular reactors for reaction intensification, controlled mass transport, and scalable operation, thereby supporting their deployment in both laboratory investigations and industrial process development.

4. Advances in Structural and Mechanical Design

There has been a periodic increase in attention to the mechanical and structural robustness of annular reactors, especially under cyclic loading, thermal cycling, flow-induced vibration, and continuous operations, while hydrodynamic performance has been kept aside. Recent advancements in the mechanical design of annular reactors have transcended mere enhancements in hydrodynamic performance, now emphasizing the assurance of structural integrity under cyclical thermal, mechanical, and vibrational stresses. CFD has been useful for predicting flow distributions, heat transfer, and wall shear stresses, but it doesn't do a good job of figuring out how materials will hold up over time or how they will deform. Combining CFD with FEM gives you more information: CFD works out the pressure and shear profiles in the fluid domain, while FEM takes into account creep, fatigue, and thermal expansion in the walls of the reactor.

The selection of a numerical framework significantly impacts predictive accuracy. The FVM-based CFD is great at keeping mass, momentum, and energy in complex shapes, but it can have trouble with structural deformation when there is a lot of FSI. FEM is harder to use for flow fields, but it lets you do stress-strain coupling and thermal deformation analyses with more accurate geometry. For example, using FEM to improve spiral fins with elliptical cross-sections lowered peak stresses and improved the flow of air inside the fins at the same time. This led to a ~40% increase in photocatalytic efficiency. But mesh resolution and solver assumptions are still major problems. Coarse meshes may not accurately predict peak stresses and localized shear, while very fine meshes (more than 1 M cells) can make calculations much more expensive. Steady-state laminar solvers work well for Re ≈ 164.2, but when flows get close to transitional regimes, turbulence models (like realizable k-ε or transition SST) make it hard to predict what will happen near walls. These trade-offs show that optimizing mechanical and structural design can't be done with just one modeling method. Instead, it needs to combine the strengths of CFD and FEM while also being aware of their weaknesses. The concentric cylindrical configuration, which makes the base of the annular design ideal for flow and heat transfer, throws some design challenges related to material creep, fatigue, thermal expansion and pressure containment [38]. The reactor longevity is guaranteed by taking care of the aforesaid factors and making it reliable in an industrial setting. SS 316 annealed steel, in particular, offers an enhanced fatigue life and makes the reactor resistant to thermal shock, which ultimately makes it preferable for use in cyclic thermal loads or chemically aggressive environments [39]. The use of these materials enables the fabrication of compact, pressure-resilient geometries with minimal warping or deformation under operational conditions. The observed enhancement in mechanical precision highlights the progressive development of contemporary numerical simulation techniques. CFD, when integrated under the FEM tools, simulate fluid structure interaction, allowing conceptual visualization of stress distribution(thermal stress distribution also), thermomechanical coupling effects and deformations [35]. The optimization of wall thickness, concentric cylinder structure and structural joints and couplings are taken combinedly taken care of by engineers. For instance, redesigning spiral fins with elliptical cross-sections has been shown to reduce peak stress concentrations while improving internal flow behaviour, leading to a 40% improvement in photocatalytic efficiency [2]. Stress hotspots are often located in the thermo-mechanical hydrodynamic CFD studies. CFD under FEM combinedly identifies these high-strain zones, particularly in transitional flow regimes where vortex flow shedding may occur. This is especially relevant in hydrogen storage reactors and thinfilm deposition systems operating near critical pressure conditions [3]. The use of filleted joints, compliant seals, and geometrical buffers to accommodate thermal expansion and reduce abrupt stress gradients is included mechanical additional enhancement. These design interventions increase mechanical resilience without compromising flow characteristics.

5. Structural and Mechanical Design Integration

Figure 2 illustrates the schematic layout of an advanced hydrodynamic annular microreactor, highlighting both the side-view and isometric perspectives to provide a comprehensive understanding of its geometry, boundary constraints, and internal flow domain. The reactor consists of two concentric cylindrical surfaces that form a narrow annular gap through which the working fluid moves. This annular configuration is specifically engineered to achieve predictable hydrodynamic behavior, enhanced surface interactions, and efficient mass and heat transfer—all essential characteristics for microreactor applications in chemical synthesis, photochemical transformations, and catalytic processes.

The side-view representation in Figure 2 emphasizes the uniform annular gap height and the axial direction of flow, bounded at the top and bottom by controlled inlet and outlet boundary conditions. These boundary conditions are critical for maintaining laminar regime stability, especially at the reactor's specified hydraulic diameter of 8 mm and overall length of 1 m. Under these dimensions, the system exhibits a Reynolds number of approximately 164.2, which is well within the laminar flow range for annular channels. The resultant pressure drop of roughly 8.76 Pa allows the reactor to function with minimal pumping energy, ensuring low operational costs and stable flow characteristics—attributes desirable for long-duration catalytic or photochemical reactions. The isometric view in Figure 2 offers deeper visualization of the reactor's internal structure, including bolt holes, mounting interfaces, and the distribution of ports for fluid entry, exit, or sensor integration. This detailed three-dimensional depiction makes it clear how the annular gap is enclosed within a mechanically robust stainless-steel shell, chosen for its corrosion resistance [36], thermal stability [16], and mechanical durability [40]. Such features ensure structural longevity even under thermal cycling and pressure fluctuations commonly encountered in microreactor environments. The geometric design also provides a favorable surface area-to-volume ratio (~250.22 m^{-1}), significantly enhancing heat exchange efficiency. This high ratio is especially important in photochemical and catalytic systems where precise thermal regulation is required to avoid hotspots or uneven reaction zones. CFD and FEM simulations further reinforce the reliability of the design. Hydrodynamic modeling confirms smooth velocity profiles, consistent shear stresses along the annular walls, and predictable residence time distribution–all outcomes of the laminar regime. Coupled FEM simulations validate the structural integrity of the annular shell by mapping stress concentrations and deformation patterns under expected temperature gradients and pressure loads. These insights guide iterative geometric refinements, ensuring the reactor maintains dimensional stability and uniform flow characteristics across a breadth of operational conditions, as reported in earlier studies [3,41].

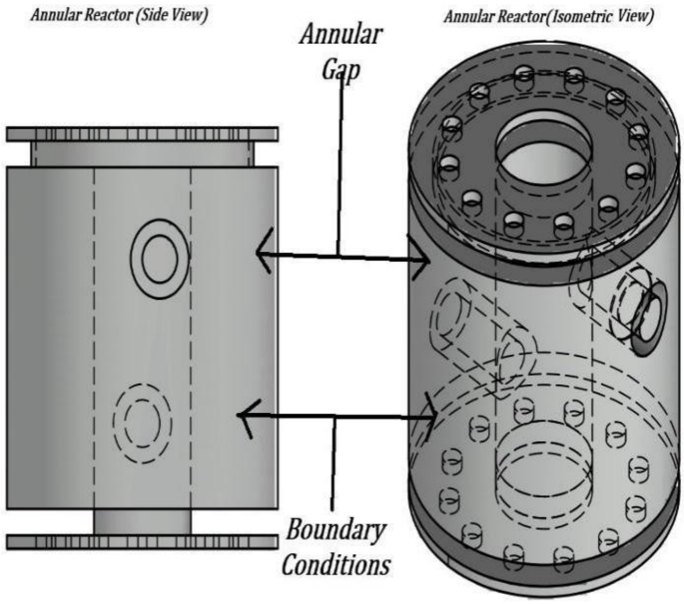

Figure 2. Schematic illustration of the advanced hydrodynamic annular microreactor.

6. Coupling Hydrodynamics with Mechanical Simulations

Figure 3 presents a detailed AutoCAD 2020 engineering drawing of the advanced hydrodynamic annular microreactor, highlighting its precise geometry, dimensional tolerances, and structural components essential for integrated CFD-FEM analysis. The figure shows both longitudinal and cross-sectional views, allowing visualization of the 800 mm reactor length, the outer diameter of 40 mm, and the inner annular channel characterized by the 32 mm internal bore. These dimensions define the annular gap through which the fluid travels, a region whose flow uniformity and shear distribution must be accurately predicted using multi-physics simulations. The longitudinal view in Figure 3 illustrates the centrally aligned annular passage, flanged end sections, and ports for fluid entry, exit, or instrumentation. Such geometric clarity is crucial for defining boundary conditions during coupled simulations. The dimensional annotations–ranging from millimeter-scale channel widths to sub-millimeter structural features–support mesh refinement strategies employed in CFD-FEM co-simulation workflows. These high-resolution geometric features are particularly important when addressing stress concentrations around sharp edges or thin-walled regions, which earlier studies have shown to require physics-controlled meshing or filleted transitions to reduce structural vulnerabilities [42,43]. The cross-sectional view of Figure 3, with its accurately dimensioned bolt-hole pattern and annular flow path, provides the structural basis for two-way FSI modeling. Modern multi-physics tools have made it possible to couple CFD-generated pressure, shear, and thermal loads with FEM deformation responses, allowing real-time assessment of how hydrodynamic forces influence mechanical strain distributions [35]. This integrated approach, unlike older one-way or uncoupled models, enables precise evaluation of how operational variations–rapid temperature cycling, fluctuating inlet velocities, or reactive heating–affect long-term durability of the annular reactor.

The computational relevance of this design becomes even more significant when considering the complexity of multi-physics simulations. Partitioned solvers, which treat CFD and FEM domains separately, provide flexibility and lower memory requirements but may struggle with convergence when high fluid-structure feedback occurs [4]. In contrast, monolithic solvers deliver enhanced accuracy by solving all governing equations simultaneously, albeit at far higher computational cost–a barrier highlighted in recent benchmarks reporting ~1 M cell meshes requiring 64 GB RAM and 16-core CPUs with 12-24 hour runtimes. These scalability challenges underscore the need for optimized geometries such as those depicted in Figure 3, where smooth transitions and symmetric sections help maintain numerical stability. The structural robustness suggested by the symmetric arrangement of bolt holes and reinforcement rings in Figure 3 is also consistent with findings from metal hydride hydrogen-storage reactor studies, where FEM-guided adjustments in wall thickness improved cycling endurance by up to 25% without compromising hydrodynamic performance [3].

Similarly, the interior clearances and surface accessibility depicted in Figure 3 support the integration of passive and active mixing structures–such as helical fins or surface micro-texturing–which have demonstrated significant gains in residence time distribution and reduced dead zones without disrupting laminar flow conditions [34,44].

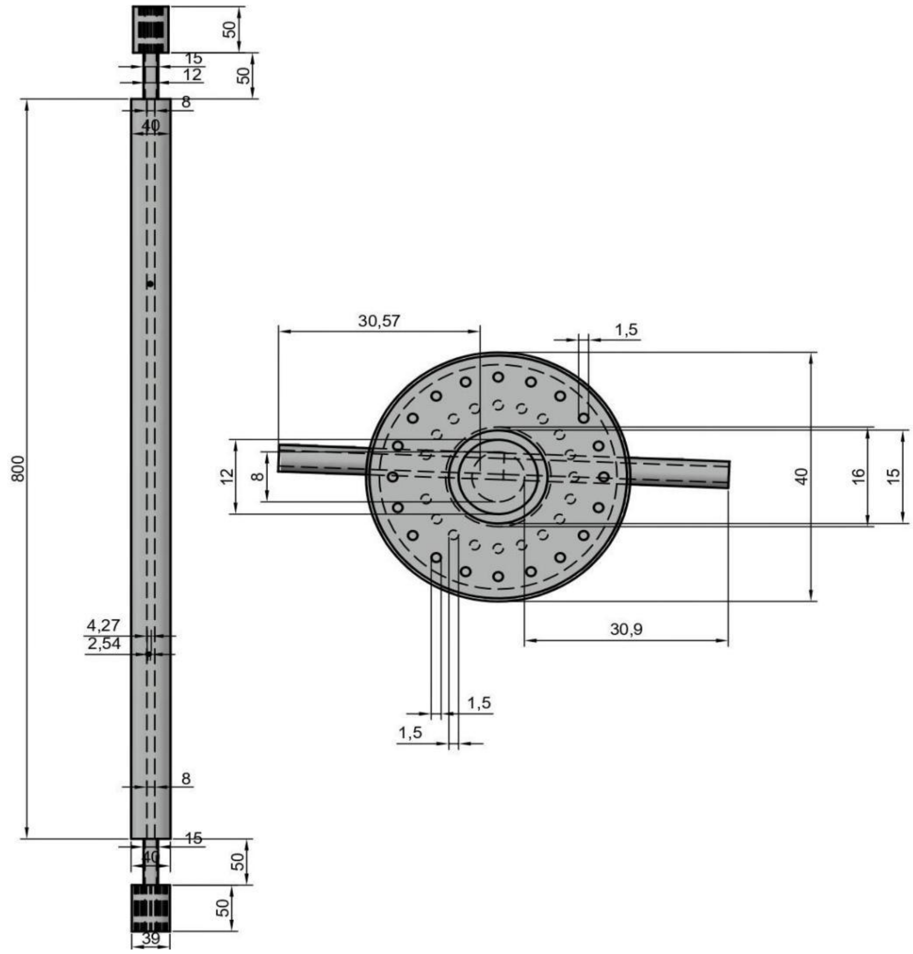

Figure 3. AutoCAD 2020 design of an advanced hydrodynamic annular microreactor.

7. Case Studies: Applications of Annular Reactor in Diverse Field

Interfacial transport has been enhanced to a great extent with the use of annular reactors, which are in extensive use in domains demanding precise control of flow and uniform thermal management [31,45]. The geometrical ability to support laminar regimes with well-defined shear and minimal axial dispersion. The highlights of this section revolve around the practical deployment of hydrogen storage by annular systems, catalytic conversion and photocatalysis, with its extensive use in nuclear energy systems, areas where structural integrity and hydrodynamic coupling have been proven as an essential component [3,4]. Hydrogen storage systems have effectively utilized annular reactors for metal hydride-based absorption processes. CFD simulations validated uniform flow distribution, while FEM confirmed structural resilience under repeated thermal cycling [46]. These configurations demonstrated energy savings and consistent absorption rates across cycles [3]. The flow inside the annular gap is genuinely laminar, as indicated by the calculated Reynolds number of 164.2 [47]. Due to the smooth and ordered laminar flow, the velocity profiles are quite predictable, and this results in less mixing compared to turbulent flow, which is a significant milestone for hydrodynamic design [48]. The laminar flow regime within the annular gap is therefore taken into consideration in both the hydrodynamic analysis and the mechanical design framework. We will be able to accurately predict pressure drop [49], wall shear, and structural integrity responses. The optimized simulation-guided annular geometry in use in hydrogen storage configurations has led to 25% improvement in reaction cycling performance. Evaluations often FEM-based under thermal loading validated the material selection of Annealed SS 304/316 [50], due to its superior corrosion resistance [50], thermal stability [16], and ease of fabrication under mechanical loads [10] instead of chrome-plated stainless steel. It is also the material of choice for guaranteeing longterm structural reliability under demanding reactor conditions due to its improved machinability [40] and mechanical workability [10], and fatigue performance, maintained integrity across multiple operational cycles. The values of Pressure drop [49] remained as low as ~ 8.76 Pa, and the system maintained consistent absorption rates with minimal energy input, confirming both mechanical and process reliability [4]. Photocatalytic water purification with Volatile Organic Compounds degradation is the field where annular reactors have succeeded with an effective platform due to their assurance of continuous reactant exposure to illuminated catalytic surfaces [51]. In simultaneous use in the nuclear and energy sectors, the annular reactors play a crucial role, in particular with annular fuel rod configurations and heat exchangers. The high surface-to-volume ratio (~ 250.22 m^{-1}) in concentric annular flow channels promotes effective heat removal with the least value of thermal resistance (~ 2.36 K/W) with predictable pressure profiles [4]. The iterative theme behind every case study is the seamless interplay between hydrodynamics and mechanical design validation [40]. A high precision customization of reactor geometry , material selection and internal features has been enabled by synchronizing simulation coupling supporting the development of scalable, modular with energy-efficient annular reactor systems targeted and optimized for specific industrial demands [46].

Table 2. Comparison of references from literature survey.

Diameter ratio	Reduced Thermal Gradients (K/W)	The hydraulic diameter	Pressure Drop	Ref.
0.625	**2.36**	**0.008 m**	**8.76Pa**	**This Paper**
0.65	2.10	0.0075 m	7.9 Pa	[56]
0.70	2.42	0.0081 m	9.1 Pa	[58]
0.60	2.25	0.0078 m	8.5 Pa	[3]

The hydraulic flow dynamics within an annular geometry at a calculated Reynolds number of 164.2 definitely confirms laminar flow conditions with the characteristics of orderly, streamline flow, marking the absence of turbulent eddies. This kind of flow regime is extensively studied in classical internal flow analyses, where the velocity distribution is parabolic and symmetric between the concentric walls, allowing the derivation of closed-form solutions for key parameters such as axial velocity, pressure drop [49], and wall shear stress [52,53]. The flow is confirmed as laminar, which makes it an ideal case for hydrodynamic coupling with mechanical simulations.

8. Research Gap and Future Scope

Previous reviews on annular reactors have primarily focused on hydrodynamic phenomena, including RTD, mass and heat transfer characteristics, and flow regime classifications, which have contributed significantly to the understanding of fluid flow patterns and transport mechanisms within these systems. These studies have established a solid foundation for predicting reactor performance and optimizing process efficiency from a fluid dynamic perspective. However, despite these advances, such reviews have largely overlooked the structural, mechanical, and material aspects that play a crucial role in the long-term stability and reliability of reactor systems operating under complex thermal and mechanical loads. A considerable number of studies have utilized CFD to analyze velocity profiles, turbulence characteristics, and transport efficiency in annular geometries. Yet, only a limited subset of this research extends to examining material endurance, deformation behavior, or wear characteristics of reactor components exposed to high shear stress or temperature gradients. The mechanical reliability of reactor walls, particularly under conditions involving creep, fatigue, and cyclic thermal stresses, has seldom been evaluated in parallel with hydrodynamic simulations. Consequently, there exists a disconnect between fluid dynamic optimization and structural integrity assessment, which can lead to incomplete understanding of system performance under realistic operational scenarios. The integration of CFD and FEM simulations through FSI modeling is an emerging yet underexplored domain in the context of annular reactors. FSI enables the simultaneous analysis of fluid forces acting on solid boundaries and the resulting structural deformation, offering a more holistic perspective on reactor design. However, the number of comprehensive studies combining these two computational domains remains limited, leaving a significant research gap in the pursuit of mechanically resilient and hydrodynamically efficient reactor systems. In addition, most existing reviews provide only superficial coverage of computational trade-offs—such as mesh resolution, solver selection, convergence criteria, and computational resource allocation—which are fundamental to ensuring simulation accuracy and scalability. These trade-offs become particularly important when transitioning from laboratory-scale analyses to industrial-scale reactor modeling, where achieving a balance between precision and computational efficiency is critical. Moreover, although a few isolated reports have discussed design enhancement strategies, such as the introduction of baffles, surface coatings, or fin configurations to improve mixing and heat transfer, there remains a lack of comparative synthesis that systematically evaluates the interdependence between performance efficiency, pressure drop, manufacturability, and maintenance requirements. The absence of such a holistic assessment limits the applicability of existing design modifications for real-world implementation. Therefore, there is a pressing need for comprehensive reviews that integrate hydrodynamic, structural, and mechanical perspectives, supported by advanced computational techniques such as multi-physics modeling and FSI frameworks. Such interdisciplinary analyses will be instrumental in developing next-generation annular reactor designs capable of withstanding prolonged operational stresses while maintaining optimal mass and heat transfer performance.

Despite considerable progress in understanding the hydrodynamics and transport phenomena within annular reactors, there remains vast potential for expanding the research scope toward integrated, multi-physics reactor modeling and structural design optimization. Future studies should emphasize the coupling of fluid dynamic simulations with mechanical and material performance analyses through advanced FSI and multi-scale modeling frameworks. Such integration will enable a more realistic representation of reactor behavior under combined thermal, mechanical, and flow-induced stresses, bridging the existing gap between hydrodynamic optimization and structural reliability. Furthermore, future investigations can focus on computational co-simulation techniques that merge CFD with FEM models to predict deformation, creep, and fatigue behavior under varying operational loads. These coupled models can provide valuable insights into the lifetime assessment and design durability of annular reactors, particularly for industrial-scale systems operating under extreme temperature and pressure gradients. Additionally, studies could explore data-driven surrogate modeling and machine learning algorithms to accelerate the optimization of reactor geometry, mesh refinement, and solver parameters—thereby balancing simulation accuracy with computational efficiency. Another promising direction involves experimental validation of computational findings through advanced diagnostics such as Particle Image Velocimetry (PIV), Laser Doppler Anemometry (LDA), and infrared thermography, which can provide critical datasets for validating CFD-FEM coupled models. These integrated experimental-computational frameworks would help refine predictive capabilities and improve the scalability of simulation outcomes from laboratory to industrial environments. Future work should also investigate design innovations such as the incorporation of micro-structured surfaces, baffle configurations, finned walls, and novel coatings, which could simultaneously enhance mixing efficiency, heat transfer rates, and anti-fouling properties. However, such modifications should be evaluated not only for their hydrodynamic benefits but also for their implications on pressure drop, manufacturing feasibility, mechanical stress distribution, and long-term maintenance requirements. In parallel, sustainability-oriented studies are required to assess the material selection, energy efficiency, and lifecycle impacts of annular reactor systems, ensuring that emerging designs align with environmental and economic objectives. This will be particularly important as these reactors find increasing applications in bioenergy production, wastewater treatment, CO_2 conversion, and other green chemical processes. Overall, the future of annular reactor research lies in the convergence of hydrodynamics, material mechanics, computational intelligence, and sustainability principles. Developing mechanically robust, energy-efficient, and computationally optimized annular reactor systems will not only enhance process performance but also expand their applicability across diverse sectors of chemical, environmental, and energy engineering.

9. Conclusion

The panoramic evaluation of annular reactor technology demonstrated in this review reveals a dynamic convergence of hydrodynamic principles and mechanical design. This review progressed into a robust strategy for addressing the evolving needs of modern process industries. The laminar flow regime has evolved throughout the reactor's operational period. This laminar flow throughout the annular regime came out as a key blueprint for achieving uniform shear stress profiles, controlled heat dissipation with minimal energy requirements. The calculated Reynolds' number of 164.2 confirms the laminar flow through the maximum part of the regime under standard conditions. This enables a predictable velocity distribution profile that supports biofilm formation, catalytic film retention, and minimal shear-induced detachment. These characteristics are also essential for enzymatic, thin-film deposition, or metal hydride reactions. Multiphysics modelling frameworks are rapidly benefiting the modern design of annular reactors, where CFD under the FEM are simultaneously integrated. Certain challenges remain unresolved despite the advancements we studied in the review. A computationally demanding subject of accurate simulations, particularly in gas-liquid systems, has limited applicability. The geometric nonlinearity, wall effects, and deviations from ideal plug flow conditions are the reasons for the non-scale-up of annular reactors. Despite that, the progress in physics or user-controlled mesh refinement techniques, adaptive solvers in the solution portal are gradually bridging this gap (also for sharp edges). The review concludes with the idea of emergence and evolution of annular reactor systems, emphasizing the value of simulation-oriented engineering for the next generation of chemical process equipment. A performance standard has been set in reactor design, the one that balances geometry, adaptability, efficiency and resilience by harmonizing advanced computational tools with hydrodynamic optimization. The developing harmony of CFD under FEM workflows, modular design strategies and novel material science affirms to restructuring of annular reactors into adaptable and multi-functional smart process units that will be not only efficient but also resilient, robust and sturdy, with equally digitally responsive. This places annular hydrodynamic reactors as a very vital component in attaining energy-efficient, eco-friendly, high-precision reactor systems for laboratories and industries of the future.

Conflicts of Interest

The authors declare no conflicts of interest.

Generative AI Statement

The authors declare that no generative artificial intelligence (Gen AI) was used in the creation of this manuscript.

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