Study of the Hydrodynamics of Wastewater Treatment Plant Reactors

A Major Qualifying Project

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By:

Maya Vartabedian

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Advisor: Stephen Kmiotek (WPI)

Sponsor: Olivier Potier (ENSIC)

Abstract

Utilizing the research I have collected, two doctoral candidates at École Nationale Supérieure des Industries Chimiques (ENSIC) in Nancy, France, are prepared to further their studies. Their main goal is to improve the design of activated-sludge based reactors for better fluid dynamics, achieved through detailed modeling using computational fluid dynamics (CFD) simulations. Additionally, they are focused on addressing urgent environmental issues like antibiotic-resistant bacteria and micropollutants. By conducting rigorous experiments and employing innovative methods, these candidates aim to develop new approaches for sustainable wastewater treatment, ensuring public health and ecological preservation for the future.

Keywords: Activated‑Sludge, Antibiotic Resistance, Chemical Reactors, Computational Fluid Dynamics, Hydrodynamics, Wastewater Treatment

Acknowledgements

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Purpose

The study of hydrodynamics holds immense significance in the realm of chemical engineering, serving as a foundational standard for understanding fluid behavior and its applications in various industrial processes. Investigating hydrodynamics is crucial for understanding intricate phenomena associated with fluid flow, turbulence, and mixing, providing essential insights for refining reactor configurations and improving operational efficiency.

During my collaboration with two PhD students, I compiled research concerning the significance of hydrodynamics in shaping reactor designs, demonstrating its essential role in shaping optimal solutions for wastewater treatment and pollutant removal.

The first student's focus on finding the optimal reactor for wastewater treatment by manipulating hydrodynamics facilitates the important role of fluid dynamics in reactor performance. By exploring the complex relationship between reactor geometry, flow patterns, and mass transfer processes, this investigation aims to identify reactor configurations that optimize the elimination of contaminants from wastewater flows using the activated sludge process. Utilizing computational fluid dynamics (CFD) modeling will provide valuable insights into the behavior of fluid flows within the reactor, allowing for a more comprehensive understanding of how changes in hydrodynamics impact pollutant transport and product distribution.

The second student will investigate the impact of turbulence and baffles on bacterial behavior and pollutant removal, emphasizing the broad scope of hydrodynamics in wastewater treatment. Through analysis of turbulence and baffles' effects on antibiotic resistance and micropollutant removal, this research aims to reveal the fundamental mechanisms of biological and chemical processes within treatment systems. With a comprehensive understanding, innovative strategies can be developed to address antibiotic resistance and improve the removal of micropollutants, thus enhancing the effectiveness of wastewater treatment technologies and environmental health.

These research efforts highlight the significance of investigating hydrodynamics in chemical engineering. By unraveling the complexities of fluid behavior and its interactions with biological and chemical processes, researchers can gain new insights into reactor design, process optimization, and pollutant removal strategies. The pursuit of hydrodynamic knowledge empowers engineers and scientists to create sustainable solutions for wastewater treatment and environmental preservation, addressing urgent challenges facing society today.

Introduction

Hydrodynamics

Hydrodynamics is the study of fluid motion and its behavior in various situations, including the flow of liquids and gases. It encompasses the principles governing the movement of fluids, such as water and air, and explores phenomena such as turbulence, viscosity, and pressure distribution. Hydrodynamic principles are applied in diverse fields, including engineering, environmental science, and meteorology. Understanding hydrodynamics is crucial for optimizing the design and performance of systems involving fluid flow and for predicting and managing natural phenomena affected by fluid dynamics (Myers, 2009).

The foundation of hydrodynamics comprehension lies within the Navier-Stokes equation, seen in Equation 1, which is a fundamental equation in fluid mechanics that describes the motion of fluid substances.

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = - \frac{\nabla P}{\rho} + \nu \nabla^2 u \qquad (1)$$

This equation governs how velocity, pressure, temperature, and other properties of a fluid vary over time and space, providing insights into the complex behavior of fluids in various environments, including chemical reactors (Hosch, 2024).

Importance in Chemical Reactors

Hydrodynamics plays a crucial role in determining the performance of chemical reactors, impacting the efficiency and effectiveness of chemical processes. The integration of hydrodynamics into reactor performance has become increasingly common in recent years due to the flow of fluids within a reactor influencing various key aspects of chemical reactions, including mass transfer, heat transfer, and reaction kinetics. Understanding and controlling these fluid dynamics are essential for optimizing reactor design, operation, and productivity.

One fundamental reason why hydrodynamics is important for chemical reactor performance is due to its influence on mass and heat transfer processes. Efficient mixing and distribution of reactants within the reactor are essential for ensuring that all reactants come into contact with each other at the molecular level, promoting faster and more complete reactions. Poor mixing can result in regions of low reactant concentration, leading to reduced reaction rates and incomplete conversions. Additionally, the distribution of temperature within the reactor affects reaction rates and selectivity, making temperature control a critical aspect of reactor design and operation.

Hydrodynamics affects the residence time distribution of reactants within the reactor, which is crucial for determining the extent of conversion and the selectivity of the desired products. Variations in flow patterns, such as stagnant zones or regions of high turbulence, can lead to non-uniform residence times and uneven reaction progress, impacting product quality and yield. By understanding and optimizing hydrodynamic conditions, engineers can ensure more uniform residence time distributions and improve the overall performance of the reactor (Sundaresan, 2013).

Altering Hydrodynamics to Improve Chemical Reactors

Hydrodynamics play a critical role in shaping reactor design and operation. Changes in flow patterns, induced by factors like reactor geometry and fluid velocity, impact the mixing and dispersion of reactants within the reactor. Reactor configurations are often fitted to promote turbulence and enhance mass transfer, crucial for achieving optimal reaction kinetics. Additionally, the controlled induction of cavitation or turbulence within reactors can intensify mixing and heat transfer, further enhancing process efficiency.

The formation of bubbles within the reactor can significantly enhance mass transfer by increasing the boundary area available for reactions. Bubbling promotes the dispersion of reactants and facilitates the diffusion of species, leading to improved reaction kinetics and product yield. Reactor designs may incorporate features such as bubble columns or spargers to enhance bubble formation and distribution, further optimizing mass transfer efficiency.

Fluid properties also significantly influence reactor behavior. Viscosity, density, and chemical composition affect fluid flow characteristics and reaction kinetics within the reactor. For instance, the presence of viscous fluids may require modifications to reactor design to mitigate flow resistance and enhance mixing. Understanding how fluid properties interact with reactor geometry can help optimize reactor performance for specific applications, such as polymerization or catalytic reactions.

Reactor shape optimization is essential for maximizing process efficiency and product quality. By altering reactor geometry to promote desired flow patterns and enhance mass transfer, engineers can achieve greater reaction kinetics and yield. Advanced reactor designs may incorporate features such as baffles, inserts, or specialized internals to manipulate fluid flow and optimize reactor performance. The integration of computational fluid dynamics (CFD) simulations allows for the virtual testing and optimization of reactor designs before physical implementation, further enhancing efficiency and reducing costs (Sun et al., 2020).

Reactors and Components

A chemical reactor serves as a crucial apparatus in industrial processes, facilitating the interaction of chemicals to produce desired products. This equipment is designed to optimize the net present value of a chemical reaction by enhancing efficiency and ensuring the optimal production of the desired output. In wastewater treatment plants (WWTP), the selection of a suitable reactor type is very important, as it directly influences the efficiency and effectiveness of the chemical processes utilized (CEW, 2020).

Chemical reactors come in various types, with the four main categories being batch reactor, semi-batch reactor, continuous stirred-tank reactor (CSTR), and plug flow reactor (PFR). Each of these reactor types possesses its own set of advantages and disadvantages, making them suitable for specific applications within WWTP (CEW, 2020).

Batch Reactor

A batch reactor functions as an enclosed vessel where chemical reactions occur, characterized by its non-continuous operation. Initially, all reactants are introduced into the reactor simultaneously. Equipped with an agitator, the vessel employs this device to thoroughly mix the reactants, promoting efficient contact and facilitating the production of desired products (CEW, 2020).

This reactor type is considered non-steady and transient, signifying that the degree of conversion within the reactor is time-dependent. The agitation process, facilitated by the agitator, ensures a high degree of uniformity throughout the batch reactor. The extent of conversion remains consistent regardless of the location within the reactor, contributing to its reliability and predictability (CEW, 2020). Figure 1 depicts an example of a batch reactor.

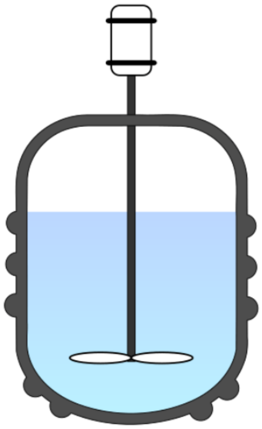

Figure 1. Schematic of a batch reactor (CEW, 2020).

The primary benefit of utilizing a batch reactor is in its versatility. This reactor type can effectively handle a diverse range of reactants within the same system, making it particularly advantageous for reactions that yield multiple products. It has a frequent application in laboratory settings for studying the kinetics of liquid-phase reaction systems (CEW, 2020).

A disadvantage of batch reactors is the substantial labor requirement for continuous tasks such as charging reactants, discharging products, and cleaning the reactor for future batches (CEW, 2020).

Semi-Batch Reactor

A semi-batch reactor, often referred to as a semi-flow reactor, represents a modification of the traditional batch reactor. Similar to a batch reactor, it operates within a closed vessel with agitators ensuring effective mixing of reactants. However, the key distinction lies in the charging process: one reactant is introduced entirely at the start, while the other is continuously added over time as the reaction progresses (CEW, 2020). Figure 2 depicts an example of a semi-batch reactor.

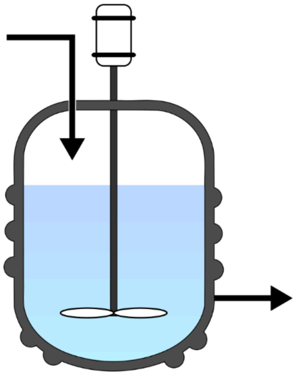

Figure 2. Schematic of a semi-batch reactor (Deaconu, 2024).

Utilizing a semi-batch reactor provides an advantage when conducting multiple reactions, giving enhanced control over product yield and selectivity. This reactor proves valuable in exothermic reactions, as the continuous introduction of the second reactant can be adjusted to effectively regulate the exothermic process (Deaconu, 2024).

When scaling up the semi-batch process, a drawback compared to continuous process reactors is the relatively higher capital costs per unit. This is attributed to the increased manpower needed for tasks such as charging and discharging reactor contents, as well as cleaning blades and reactors (Deaconu, 2024).

CSTR

A Continuous Stirred Tank Reactor (CSTR), operating in a closed tank with an agitator, ensures thorough mixing of reactants, distinguishing it from a batch reactor. Reactants enter at a specific mass flow rate, undergo reaction for a duration determined by the space time of the reactor, and exit as products at the same mass flow rate (CEW, 2020).

CSTRs are characterized by steady-state operation, meaning the extent of conversion remains constant and is not time-dependent. The agitator contributes to uniform concentration throughout, ensuring that the extent of conversion is independent of the reactor's location but influenced by reactor volume (CEW, 2020). Figure 3 depicts an example of a CSTR reactor.

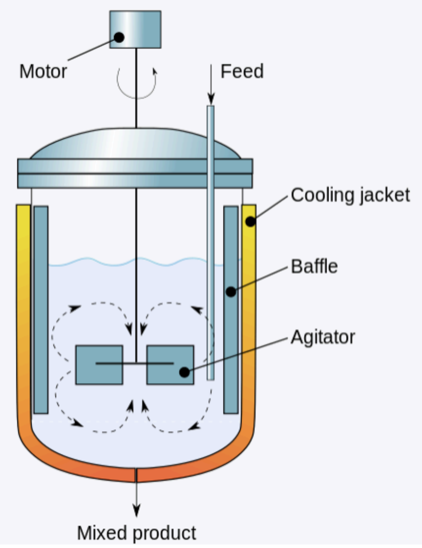

Figure 3. Schematic of a CSTR (Deaconu, 2024).

The primary benefit of employing a CSTR in industries is its capacity to generate substantial product quantities. As a continuous steady-state reactor, it can operate continuously for extended hours without the constant need for labor (Deaconu, 2024).

A drawback of utilizing a CSTR arises when dealing with reactions exhibiting slow kinetics, as it necessitates an impractically large reactor volume. The fabrication and operational costs may render it economically unfeasible, leading to the preference of using a batch reactor in such cases (CEW, 2020).

PFR

The model for a Plug Flow Reactor (PFR) characterizes chemical reactions within continuous, flowing systems with cylindrical geometry. The flow of fluid in a PFR is represented by an idealized model where it moves through the reactor in a series of extremely thin and coherent "plugs," each exhibiting a uniform composition. These plugs progress in the axial direction of the reactor, with distinct compositions from those preceding and succeeding them. The crucial assumption is that, as a plug traverses the PFR, radial mixing is perfect, while axial mixing is non-existent (neither with the element upstream or downstream). Each plug is treated as an independent entity, resembling an infinitely small batch reactor with virtually no volume for mixing (Vapourtec, 2023). Figure 4 depicts an example of a PFR reactor.

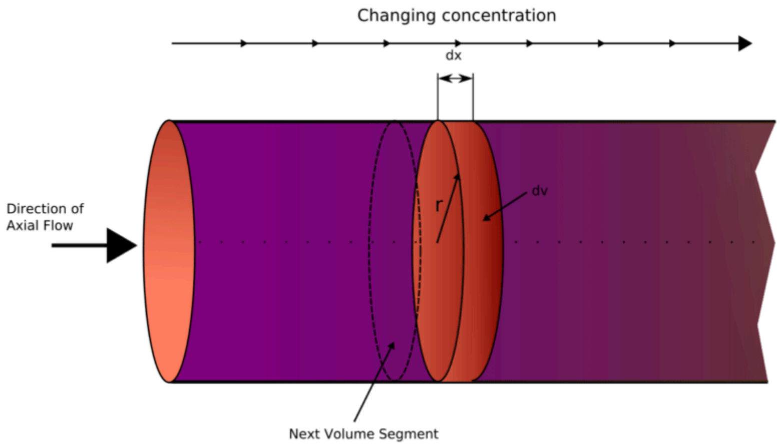

Figure 4. Schematic of a PFR (Deaconu, 2024).

The advantage of a PFR over aforementioned reactors lies in its smaller volume requirement for the same space time and conversion level. This implies a reduced space footprint for the reactor. Additionally, when comparing equal reactor volumes, the PFR achieves a higher level of conversion than the CSTR. PFRs are frequently employed to investigate the kinetics of gas-phase catalytic reactions (CEW, 2020).

A drawback of using a PFR is the challenge in controlling temperature gradients, particularly when conducting exothermic reactions. Additionally, the operational and maintenance costs associated with a PFR are higher compared to a CSTR (Deaconu, 2024).

Use of Baffles

In a chemical reactor, baffles are commonly affixed to the interior walls to enhance mixing, therefore improving heat transfer and potentially increasing chemical reaction rates. This heightened mixing efficiency results from vigorous top-to-bottom fluid mixing within the vessel. In the absence of baffles, achieving the desired mixing may take longer, or adequate blending of fluids might be unattainable (The Engineering Concepts, 2019).

Baffles function by disrupting the flow pattern and facilitating top-to-bottom flow within the tank. When dealing with solid suspensions in a large cylindrical tank without baffles, a swirling flow pattern is often observed. This is undesirable as solid particles may accumulate at the tank's bottom instead of being thoroughly mixed into the solution. Introducing baffles ensures top-to-bottom flow within the tank (Enduramaxx, 2021).

The formation of a vortex, induced by the agitator's rotation, can negatively impact mixing in a reactor vessel. Baffles in the reactor vessel disrupt the circulating flow pattern, preventing vortex formation and enhancing overall mixing (Spinchem, 2024).

BOD_5 and COD removal

Gathering and analyzing measurements for chemical oxygen demand (COD) and biological oxygen demand (BOD_5) removal allows the wastewater to be safely discharged into the environment and ensures a clean and sustainable approach devoid of pollution. COD measures the water's ability to consume oxygen during the breakdown of organic substances (Parry, 2022). BOD_5 evaluates the quantity of dissolved oxygen required by aerobic microorganisms for the decomposition of organic matter in water, following a 5-day incubation period (Fabregas, 2023). The COD indicates the total of all dissolved substances, the BOD_5 the amount of biodegradable substances (ClearFox, 2022).

The $\frac{BOD_5}{COD}$ ratio provides insight into the origin and nature of organic pollution. Typical values for the $\frac{BOD_5}{COD}$ ratio are detailed in table 1. The untreated municipal wastewater typically falls within the range of 0.3 to 0.8. If the ratio is greater than 0.5 for untreated wastewater, the waste is deemed readily manageable through biological treatment methods. If the $\frac{BOD_5}{COD}$ ratio is less than 0.3, either the waste may contain certain toxic elements or the utilization of acclimated microorganisms may be necessary for stabilization (EMWATER, 2024).

Table 1. Ratios of BOD_5/COD based on type of wastewater.

Type of Wastewater	**BOD_5/COD**
Untreated	0.3 - 0.8
After primary settling	0.4 - 0.6
Final effluent	0.1 - 0.3

BOD_5 serves as a measure of water quality and the degree of organic contamination present. Industries producing wastewater with organic substances or pollutants may need to eliminate BOD_5 to ensure environmental protection and compliance with regulations. Effective wastewater treatment is crucial for managing BOD_5 and COD, safeguarding the health of waterways. Maintaining low BOD_5 levels guarantees that water discharged from a treatment facility is safe and clean for the environment (Fabregas, 2023).

Utilizing activated sludge stands as a prevalent method for wastewater treatment, and increasing aeration is vital for reducing BOD_5 in this process. The effectiveness of reducing BOD_5 within an aeration tank relies on air diffusers, facilitating the delivery of oxygen to beneficial bacteria. These diffusers maintain the vitality of beneficial bacteria in the activated sludge, enabling the decomposition of waste. In the activated sludge process, the integration of beneficial bacteria converts pollutants into waste sludge, later subjected to filtration and disposal through the secondary clarifier (Frankel, 2024).

Releasing untreated wastewater into the environment has a high potential to cause severe pollution. Microorganisms naturally present in wastewater view the pollution as a food source, leading to an excessive multiplication of microbes in public waters. Since microorganisms require oxygen to respire organic pollutants and multiply, they deplete the water's oxygen and negatively impact other living organisms (ClearFox, 2022).

Background #1

Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze complex equations related to the flow of fluids, such as gases and liquids. CFD is widely used in engineering, physics, and various industries to simulate fluid flow and heat transfer problems in a virtual environment. Engineers can acquire valuable understandings of fluid dynamics, enhance designs, and make well-informed choices to enhance the effectiveness and efficiency of various engineering systems (FasterCapital, 2023a).

Conservation Laws

Certain fundamental concepts of fluid dynamics that are crucial for understanding CFD include principles of conservation laws, fluid properties, flow patterns and boundary conditions (FasterCapital, 2023a).

Fluid dynamics is guided by three fundamental conservation laws: mass, momentum, and energy. The conservation of mass asserts that the mass of a fluid remains constant in a closed system, illustrated in Equation 2 (Bird et al., 2007), where V and D_{AB} are constants.

$$- D_{AB}\nabla^2 C_A + V\nabla C_A + \frac{\partial C_A}{\partial t} - R_A = 0 \tag{2}$$

Momentum conservation links forces to fluid acceleration, shown in Equations 3, 4 and 5 (Bird et al., 2007), each corresponding to a plane in the Cartesian coordinate system. Solving these equations with equation 2 will result in the distribution of the mixed fluids in the resulting stream.

$$\frac{u\partial u}{\partial x}+\frac{v\partial u}{\partial y}+\frac{w\partial u}{\partial z}+\frac{\partial u}{\partial t}=X-\frac{1}{\rho}\frac{\partial \rho}{\partial x}+\frac{\mu}{\rho}\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \quad (3)$$

$$\frac{u\partial v}{\partial x}+\frac{v\partial v}{\partial y}+\frac{w\partial v}{\partial z}+\frac{\partial v}{\partial t}=Y-\frac{1}{\rho}\frac{\partial \rho}{\partial y}+\frac{\mu}{\rho}\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right] \quad (4)$$

$$\frac{u\partial w}{\partial x}+\frac{v\partial w}{\partial y}+\frac{w\partial w}{\partial z}+\frac{\partial w}{\partial t}=Z-\frac{1}{\rho}\frac{\partial \rho}{\partial z}+\frac{\mu}{\rho}\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right] \quad (5)$$

The conservation of energy accounts for energy transfer in a fluid system, seen in Equation 6 (Bird et al., 2007), where viscous heating is neglected. Comprehending these laws is vital for precise fluid behavior modeling in CFD simulations.

$$-k\nabla^2 T+\rho C_p V\nabla T+\rho C_p\frac{\partial T}{\partial t}-Q=0 \quad (6)$$

To simulate fluid behavior accurately, understanding key fluid properties is critical. Properties like density, viscosity, and compressibility play important roles to allow engineers to model fluid behaviors accurately in simulations (FasterCapital, 2023a).

Fluid flow can display different patterns, laminar and turbulent. Laminar flow is smooth traveling in parallel layers with minimal mixing, while turbulent flow is irregular and mixed. The transition between the categorized flows depends on factors like velocity, viscosity, and system geometry. Understanding these patterns is crucial for predicting fluid behavior and optimizing designs to reduce energy losses or enhance mixing efficiency (FasterCapital, 2023a). To ensure product quality, consistency, and cost-effectiveness, achieving optimal mixing efficiency in the system is important. A proven solution to improve mixing performance is static mixer nozzles, ensuring more efficient, homogeneous mixing of the fluid (Lovelylzp, 2023).

Boundary conditions are pivotal in fluid dynamics simulations, defining fluid behavior at computational domain boundaries with parameters like velocity, pressure, and temperature. Accurate definition of boundary conditions is essential for reliable simulation results (FasterCapital, 2023a).

Effective CFD Simulation

To generate a reliable CFD simulation, it is essential to accurately depict the geometry and implement appropriate meshing. Simplify and clean the geometry, and use a suitable meshing technique for the system. Meshing involves dividing the domain into smaller elements, discretizing the fluid flow equations. This enables engineers to computationally create predictive models of real-world scenarios. The simulation's performance improves with a more precise mesh. An example of a CFD model of a reactor can be seen in Figure 5 (Spatial Team, 2022).

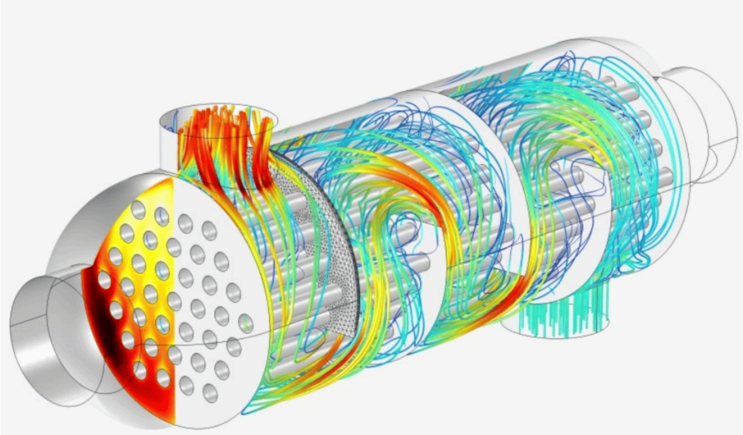

Figure 5. Computational Fluid Dynamics (CFD) model illustrating fluid flow, heat transfer, and mass transfer within the reactor (COMSOL, 2021).

Advantages of CFD

CFD empowers designers and engineers to offer intricate visual representations of fluid flow patterns and make precise predictions, particularly in intricate flow systems. This simulation provides the advantage of detecting potential issues, refining designs, and enhancing overall performance prior to the construction of physical prototypes. The ability to simulate online significantly reduces costs and saves time in the engineering design process. Traditional physical testing methods are often time-consuming and costly, involving the creation of prototypes before optimization and the execution of numerous experiments. Therefore, CFD enables visualization without the need for traditional physical testing (Martin, 2022).

CFD simulations offer a comprehensive understanding into the flow dynamics and physical occurrences within a system, enabling engineers and scientists to make well-informed decisions in the design process. They enable the exploration of various design alternatives, allowing engineers to enhance designs for specific goals, such as maximizing efficiency or minimizing emissions. Furthermore, CFD can assess design safety and anticipate potential hazards, enabling proactive measures to mitigate risks (Martin, 2022).

Limitations of CFD

CFD has inherent limitations as it depends on assumptions and simplifications that might not fully represent the intricacies of real-world fluid flow. To ensure accuracy and reliability, it is typically necessary to validate CFD models by comparing simulation results with experimental data. However, validation and verification pose challenges, particularly in cases of complex flows or limited availability of experimental data. Additionally, resource limitations, such as inadequate equipment or budgetary constraints, may inhibit the validation process using physical models in a laboratory setting (FasterCapital, 2023a). Conducting CFD simulations can require significant computational power, necessitating access to substantial resources such as high-performance computing clusters or cloud computing services. Constraints in computational resources may limit the scale and intricacy of simulations that can be executed (Martin, 2022).

Turbulence modeling poses a constant challenge, given the intricate nature of turbulent flows. Various turbulence models have been created, each with its own set of assumptions and constraints. Choosing the right turbulence model for a particular application requires thoughtful consideration and validation against experimental data. However, the complexity of turbulent flows introduces difficulties in achieving convergence, where the solution stabilizes with further iterations. Numerical errors can affect both the accuracy and convergence of results, making the difficult selection of turbulence models even more crucial, particularly for complex flows or when employing specific numerical techniques (FasterCapital, 2023a).

Relation to Chemical Engineering

In the realm of chemical engineering, engineers employ simulations to scrutinize fluid flow dynamics and chemical reactions. This comprehensive approach enables the identification of potential challenges, including the detection of dead zones or undesirable mixing phenomena within the system. Engineers can then implement necessary modifications to enhance system performance and efficiency.

In the chemical and process industry, where reliability is paramount, the validation of CFD results with experimental data becomes essential. This validation process ensures that the simulated scenarios align accurately with real-world conditions. It plays an important role in confirming the precision of CFD models and, as a result, instills confidence in the insights derived from these simulations (FasterCapital, 2023a).

Anoxic Reactors

Anoxic conditions pertain to environments lacking molecular or free oxygen (O_2), while bound oxygen may still be present. The term "anoxic" specifically denotes the condition of the environment rather than referring to microorganisms and their associated processes (Frankel, 2020).

Despite the absence of molecular oxygen in anoxic conditions, nitrates or nitrites may still be present. Both nitrates (NO_3) and nitrites (NO_2) inherently contain bound oxygen within their molecular structures. An environment can be classified as anoxic as long as it lacks free oxygen, even if it includes these compounds (Frankel, 2020).

In wastewater treatment, anoxic zones play a crucial role in nitrogen removal. Some wastewater contains elevated levels of nitrates and nitrites, necessitating their breakdown to prevent nutrient pollution during effluent discharge into the environment (Frankel, 2020).

Within anoxic zones, bacteria are responsible for breaking down nitrogen products. During this process, the separation of molecules releases oxygen, which is vital for the thriving of these bacteria. Interestingly, the natural biodegradation of nitrogen products in anoxic tanks, such as denitrification basins, eliminates the need for additional oxygen supplementation from diffusers or surface aerators. This release of oxygen through the biodegradation process emphasizes the efficiency of anoxic conditions in wastewater treatment systems (Frankel, 2020). The overall denitrification process can be seen in Equation 7 (Lim et al., 2018).

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \tag{7}$$

Nitrates

Unabsorbed nutrients like nitrogen, when not utilized by plants, escape into the environment and transform into pollutants if their concentration becomes excessive. One specific concern is the elevated levels of nitrate in groundwater, which can jeopardize both the environment and human health (EEA, 2023).

Nitrates, represented by the negative nitrate ion (NO_3^-), frequently combine with positive metal ions, such as sodium and copper, to create diverse salts. These compounds find applications ranging from essential components in fertilizers and explosives to roles in food preservation and pharmaceutical manufacturing, establishing nitrates as prevalent industrial materials. Nevertheless, the release of nitrates into the environment (air, water, and soil) as industrial waste can lead to significant issues. Exposure to nitrates has been associated with various diseases, including cancer and thyroid disorders. For instance, a recent study demonstrated a correlation between nitrate exposure and an elevated risk of gastric cancer (Picetti et al., 2022). Furthermore, an excess of nitrates in water can stimulate algal blooms, potentially causing entire fish populations to relocate or die (Zhan, n.d.).

The World Health Organization has established a safety threshold for nitrates at 50 mg/L (Francis, 2022). When wastewater contains an excess of nitrates, a detrimental impact on oxygen levels ensues, as nitrates tend to consume oxygen molecules, impairing the proper functioning of the body. Conversely, nitrates play a crucial role in preventing antibiotic resistance. The absence of nitrates can lead to the demise of antibiotic molecules, rendering them ineffective in supporting the body's defense mechanisms. Thus, maintaining a delicate balance between the absence of nitrates and an excessive presence is important for overall success in health management. Achieving this equilibrium ensures optimal oxygen levels and supports the efficacy of antibiotics in safeguarding the body against potential threats (ATSDR, 2013).

Degradation of Nitrates

The degradation of nitrates in anoxic reactors is a process that occurs in the absence of oxygen. Anoxic conditions are created purposely in these reactors to facilitate the reduction of nitrates to nitrogen gas (N_2) or other harmless nitrogen compounds. This process is typically part of wastewater treatment strategies, where nitrate removal is essential to prevent environmental pollution and to meet regulatory standards.

The degradation of nitrates in anoxic reactors involves denitrifying bacteria, which are microorganisms capable of using nitrates as a substitute for oxygen in their respiratory processes. The overall denitrification process can be summarized in four steps and shown in Equation 7 above.

1. $NO_3^- \rightarrow NO_2^-$: Nitrates present in the wastewater are converted to nitrites through the activity of denitrifying bacteria.
2. $NO_2^- \rightarrow NO$: Nitrites are then further reduced to nitric oxide in the absence of oxygen.
3. $NO \rightarrow N_2O$: Nitric oxide undergoes additional reduction to form nitrous oxide, another intermediate compound in the denitrification process.
4. $N_2O \rightarrow N_2$: The final step involves the reduction of nitrous oxide to nitrogen gas, which is relatively inert and harmless.

The success of the denitrification process in anoxic reactors depends on several factors, including the availability of suitable organic carbon sources for the denitrifying bacteria and the proper control of environmental conditions such as pH and temperature.

This controlled degradation of nitrates is crucial for mitigating the negative environmental impacts associated with high nitrate concentrations, such as groundwater contamination and the promotion of harmful algal blooms. It is an important aspect of wastewater treatment systems designed to ensure compliance with water quality standards and environmental regulations (Rossi et al., 2014).

Background #2

Antimicrobials and Antibiotic Resistance

Antimicrobial Resistance

Antimicrobials, which encompass antibiotics, antivirals, antifungals, and antiparasitics, are medications utilized for the prevention and treatment of infectious diseases across humans, animals, and plants. Antimicrobial Resistance (AMR) arises when bacteria, viruses, fungi, and parasites no longer respond to these medications. For bacteria, this is made possible by antibiotic resistance genes (ARG) (Uluseker et al., 2021). Consequently, the effectiveness of antibiotics and other antimicrobial drugs diminishes, leaving infections challenging or even impossible to treat. This escalation in drug resistance enhances the risk of disease spread, severe illness, disability, and death. The global surge in antibiotic resistance (AR) presents a substantial threat, reducing the efficiency of conventional antibiotics against common bacterial infections. AMR is a natural process that evolves gradually through genetic alterations in pathogens. Human activities, particularly the misuse and excessive use of antimicrobials for treating, preventing, or controlling infections in humans, animals, and plants, expedite the emergence and spread of AMR (World Health Organization, 2023).

Evolution of AMR

There are four primary genetic mechanisms through which antibiotic resistance evolves, outlined as follows.

1. The primary site comprises the human and animal microbiota, encompassing over 500 bacterial species, where therapeutic or preventive antibiotics exert their effects.
2. The secondary site involves settings such as hospitals, long-term care facilities, farms, or any crowded environment where susceptible individuals are exposed to bacterial exchange.

3. The tertiary site pertains to wastewater and various biological residues originating in the secondary site, including lagoons, sewage treatment plants, or compost toilets. Here, bacterial organisms from different individuals have the opportunity to mix and genetically react.
4. The fourth site encompasses soil, surface, or groundwater environments, where bacterial organisms from preceding sites mix and interact with environmental organisms (Baquero et al., 2008).

The potential to diminish the evolvability of antibiotic resistance depends on humans' capacity to regulate the flow of bacterial clones, active antimicrobial agents, and genetically encoded biological information across these genetic sites. Enhancing our understanding of efficient barrier measures is important to prevent the introduction of resistant and pathogenic bacteria into the environment (Baquero et al., 2008).

Removal of ARGs from Wastewater

Recently, increased attention has been directed towards exploring techniques for detecting and eliminating ARGs, along with methods for removing various micropollutants such as detergents, pesticides, pharmaceuticals, and personal care products (Alam et al., 2021).

Membrane bioreactors (MBRs) have shown promise in enhancing ARG removal compared to traditional activated sludge reactors. This improved performance is attributed to MBRs' ability to eliminate bacteria, facilitated by additional filtration through the membrane. While the authors (Uluseker et al., 2021) acknowledged the passage of DNA through membranes, they emphasized that membrane filtration processes can serve as an additional barrier and post-treatment option for effluent, reducing ARG release from WWTP effluents. The design of WWTPs should be customized based on this understanding, specifically addressing the requirements of the particular wastewater to ensure the effective removal of antibiotics and ARGs, thereby preventing the spread of antibiotic resistance in the receiving water body (Uluseker et al., 2021).

The performance of redox gradient aerobic, anoxic, and anaerobic activated sludge reactors, along with their sequencing in a WWTP, significantly influences ARGs removal (Alam et al., 2021). Research indicates that anoxic and anaerobic treatment stages in the WWTP lead to a decrease in ARG concentrations, while aerobic treatment has the opposite effect, increasing ARG levels in wastewater. The introduction of oxygen during aerobic treatment may create conditions that stimulate the survival and propagation of bacteria carrying antibiotic resistance traits. This highlights the importance of understanding these reactor dynamics to develop effective strategies for preventing the release of ARGs into the environment (Uluseker et al., 2021).

Activity of Bacteria

Germs, which encompass bacteria, fungi, parasites, and viruses, seen in Figure 6, are minuscule organisms that play diverse roles in the ecosystem.

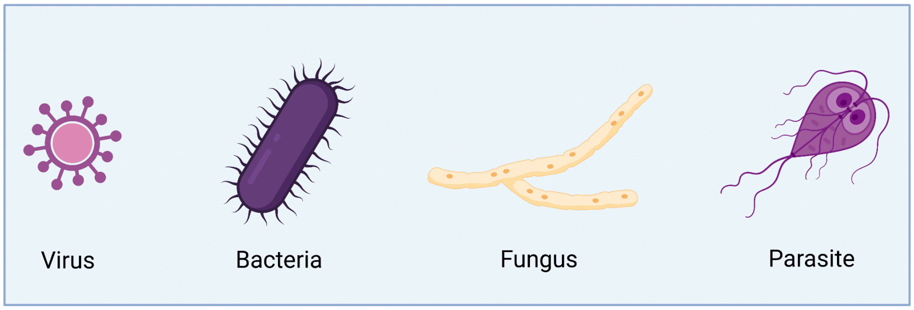

Figure 6. Overview of the four main types of germs: fungi, parasites, viruses, and bacteria (Smore Science, n.d.).

While the majority of bacteria are benign or even beneficial to human health, a subset known as pathogens can instigate infections. Antibiotics serve as effective weapons against bacterial infections, yet their misuse contributes to the emergence of antibiotic-resistant strains.

The abuse and overuse of antibiotics exert pressure on bacteria, prompting them to adapt through mechanisms of resistance. As antibiotics eliminate both harmful and beneficial bacteria, surviving strains with resistance traits encoded in their DNA propagate and proliferate. This genetic information, dictating the production of specific proteins, enables bacteria to withstand the attack of antibiotics.

Some bacterial strains develop a collection of resistance mechanisms, rendering conventional antibiotic treatments ineffective. This situation raises significant concerns, as it may result in the emergence of infections resistant to medical intervention. The transfer of resistance traits between bacterial species, facilitated by genetic exchange mechanisms, further compounds the challenge of combating antimicrobial resistance (CDC, 2022).

Genes

Genes, fundamental components of life, play a central role in the development, functioning, and adaptation of organisms. Specifically, in the context of bacteria, genes take on a critical role in the development and spread of antibiotic resistance. The mechanisms responsible for antibiotic resistance are often embedded within the genetic structure of bacteria, illustrating the fundamental connection between genes and the responses of microorganisms to antimicrobial challenges (Ding & He, 2010).

In the realm of antibiotic resistance, bacteria exhibit inherent resistance due to genes naturally having resistance to specific antibiotics. This innate defense mechanism likely evolved as a response to challenges from other microorganisms in their environment. This inherent resistance, however, poses limitations on the effectiveness of particular antibiotics against specific bacterial strains (Sánchez-Baena et al., 2021).

The use and misuse of antibiotics create a selective pressure favoring the survival and proliferation of bacteria carrying resistance genes. With the application of antibiotics, susceptible bacteria are eliminated, enabling resistant strains to thrive and reproduce. This selective advantage accelerates the dissemination of antibiotic resistance within bacterial populations (Ding & He, 2010).

Additionally, bacteria can acquire resistance genes through diverse mechanisms like mutation or horizontal gene transfer. Horizontal gene transfer facilitates the exchange of genetic material, including resistance genes, among bacteria in their environment (Ding & He, 2010).

The phenomenon of multidrug resistance (MDR) further underscores bacterial adaptability. MDR occurs when bacteria possess multiple resistance genes, posing challenges in treating infections with conventional antibiotic procedures (Sánchez-Baena et al., 2021.

Mobile Genetic Elements

Mobile genetic elements (MGEs) play a significant role in the acquisition, spread, and persistence of antibiotic resistance in bacteria. These elements contribute to the adaptability of bacterial populations and their ability to evolve rapidly in response to antibiotic exposure.

Plasmids are a type of MGE and play a crucial role in the dissemination of antibiotic resistance genes among bacteria. Plasmids are small, circular DNA molecules that can replicate independently of the bacterial chromosome. They often carry genes encoding resistance to antibiotics. Through horizontal gene transfer, plasmids can be transferred between bacteria, spreading antibiotic resistance within bacterial communities (Haavisto, 2023).

Transposons are another class of MGE that are DNA segments and can move within the bacterial genome. These elements can carry antibiotic resistance genes, allowing them to be integrated into or extracted from the bacterial chromosome. Transposons contribute to the rapid evolution of antibiotic resistance by facilitating the movement of resistance genes within and between bacterial genomes (Babakhani & Oloomi, 2018).

Integrons are genetic elements that can capture and express gene cassettes, including those encoding antibiotic resistance. Bacteria with integrons can acquire new resistance genes through integron-mediated recombination. Integrons are often found in clinical settings and contribute to the development of multidrug resistance by allowing bacteria to accumulate multiple resistance genes (Sabbagh et al., 2021).

MGEs can play a role in biofilm formation, providing a protective environment for bacteria. A biofilm is a complex and structured community of microorganisms, primarily bacteria, that adhere to surfaces and are embedded in a self-produced extracellular matrix. This matrix acts as a physical barrier, limiting the penetration of antibiotics into the bacterial community, enhancing bacterial resistance to antibiotics. MGEs may facilitate the exchange of genetic material within biofilms, contributing to the persistence of antibiotic resistance (Rasul Pajohesh et al., 2022).

Micropollutants

Micropollutants (MPs) are particles with potential hazards found in water bodies at low concentrations, typically less than one microgram per liter. These particles originate from everyday products, including industrial chemicals, pharmaceuticals, cosmetics, pesticides, and hormones, as illustrated in Figure 7. The diverse range of these substances presents a significant challenge in assessing and controlling micropollutants. Moreover, MPs have the capacity to transform into other compounds, potentially becoming more mobile and toxic than the original substance (Bofill, 2023).

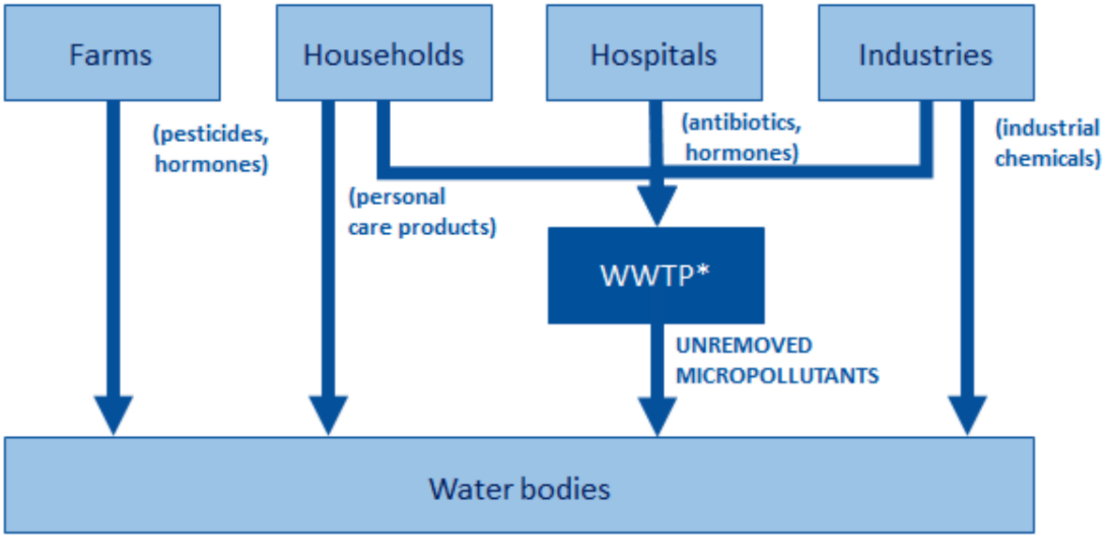

Figure 7. Pathways of micropollutants into water bodies (Bofill, 2023).

Antibiotics belong to a category of micropollutants that raise significant concerns. The discovery of antibiotics is a positive advancement in medical history, and their extensive use in human and farm animal healthcare has played a crucial role in treating bacterial infections over the years. Unfortunately, the effectiveness of antibiotics is diminishing due to the emergence of antimicrobial resistance. Antibiotic-resistant bacteria are released into the sewer system or introduced into the water cycle, with farms contributing significantly since 73% of all globally used antibiotics are utilized in animal rearing. Consequently, WWTPs become a channel for the dissemination of antibiotic-resistant bacteria to the general population, raising public concerns (Bofill, 2023).

Due to their small size and low concentrations, micropollutants can easily pass through wastewater filters, rendering them resistant to removal by conventional WWTPs (Luterbacher, 2016). The removal rate for many micropollutants in these treatment plants is below 40%. Although some pharmaceuticals exhibit high removal rates, bacterial treatment and biological degradation during the secondary treatment process in wastewater plants can result in the formation of alternative compounds, which may pose their own set of hazards (Prabakaran, 2023).

The growing trend of using treated wastewater for irrigation, particularly in water-scarce nations, emphasizes the importance of eliminating micropollutants from the water (Rogowska et al., 2019).

Adverse Impacts of Micropollutants

Despite being present in low concentrations, micropollutants can have significant repercussions on life in and around water bodies. Endocrine disrupting compounds (EDCs), a subset of micropollutants, are suspected to be connected with altered reproductive functions in both men and women. They are also associated with an increased incidence of breast cancer, abnormal growth patterns, and neurodevelopmental delays in children, along with changes in immune functions. Furthermore, other micropollutants like polyfluoroalkyl substances, commonly found in cleaning products, Teflon pans, firefighting foams, and various household items, can accumulate and persist in the human body for an extended time. This accumulation is known to result in adverse health effects, including impacts on the immune system, disruptions in thyroid hormone function, and potential cancer risks (Bofill, 2023).

Fate and Removal of Micropollutants

Despite their nearly undetectable concentrations, typically ranging from low to subparts per billion (ppb), the presence of MPs in aquatic systems has been linked to disadvantageous effects in organisms, including interfering with hormones, genetic mutations, and damaging genes (Das et al., 2017).

Municipal WWTPs utilize primary, secondary, and occasional tertiary treatment processes to effectively address incoming wastewater, designed to eliminate a majority of suspended solids, dissolved organics, and nutrients. During primary treatment, coagulants like alum, ferric chloride, polymers, and polymeric coagulant aids are applied to eliminate colloidal and suspended particulates, aiding in the removal of organics attached to dissolved humic substances and particles. The secondary treatment involves the aerobic removal of dissolved organics by a consortium of suspended micropollutants. The thickened sludge from the primary and secondary clarifiers undergoes anaerobic digestion (biosolids) before disposal. In certain locations, final treatment of the effluent involves tertiary processes such as activated carbon adsorption, ozonation, or filtration to eliminate trace concentrations of organics (Lawshan Habib et al., 2022).

Fate of Micropollutants

The adsorption of MPs onto suspended solids plays a crucial role in both primary and secondary treatment units of wastewater. This adsorption is driven by hydrophobic interactions between the aliphatic and aromatic groups of the compounds, interacting with the fat and lipid fractions in primary sludge, and the lipophilic cell membrane of microorganisms in secondary sludge (Das et al., 2017).

The modeling of MP adsorption onto sludge is conventionally approached using a linear equilibrium model, represented by Equation 8.

$$C_{ads} = K_d C_{ss} C_{dis} \tag{8}$$

where C_{ads} is the adsorbed concentration of the MP (g/L), C_{ss} is the suspended particulate concentration (g/L), C_{dis} is the dissolved concentration (g/L), and K_d is the adsorption constant (L/gss). K_d has been proposed as a relatively accurate indicator of adsorption for compounds with a value below 300 L/kg, where the adsorption onto secondary sludge is insignificant (Das et al., 2017).

Removal of Micropollutants

In a typical WWTP, the fate processes for MPs involve adsorption on suspended particulates, dissolved humic substances, primary and secondary sludge. The removal processes encompass coagulation and sedimentation, biodegradation, adsorption, advanced oxidation, and membrane filtration (Das et al., 2017).

Coagulation and Sedimentation of Micropollutants

The coagulation process operates by destabilizing colloids/emulsions through the application of coagulants, such as metal salts or synthetic organic polymers. This destabilization occurs through mechanisms like double-layer compression, adsorption and charge neutralization, trapping of particles in precipitate, and adsorption with interparticle bridging. Widely used in wastewater treatment plants, coagulation-flocculation processes enhance overall efficiency by facilitating the removal of suspended solids, colloids, and specific dissolved organics that do not settle spontaneously, as shown in Equation 9 (Das et al., 2017).

$$\%\, removal = \left(\frac{K_d C_{ss}}{1+K_d C_{ss}}\right) E_{TSS} \tag{9}$$

where K_d is the adsorption constant (L/gss), C_{ss} is the suspended particulate concentration (g/L), E_{TSS} is the removal efficiency (%) of total suspended solids (TSS) during coagulation.

During the coagulation-flocculation process, compounds with high adsorption properties undergo substantial removal, achieving efficiencies of around 70%. In contrast, compounds with lower K_d values experience a lesser reduction, typically around 25% (Das et al., 2017).

Biodegradation of Micropollutants in Secondary Treatment

Conventional municipal WWTPs often struggle to effectively remove complex MPs through biodegradation and/or biotransformation. Removal efficiencies vary widely for different compounds and under different operational conditions such as aerobic, anaerobic, anoxic, sludge retention time (SRT), pH, redox potential, and water temperature (Lawshan Habib et al., 2022).

MBRs show higher effectiveness than conventional activated sludge (CAS) processes. MBRs integrate biological treatment with membrane filtration, using micro and ultrafiltration. The removal efficiency for numerous compounds ranges widely, from 0% to 98% in CAS and between 15% and 94% in MBRs (Das et al., 2017).

When dissolved concentrations are low, the biodegradation and/or biotransformation kinetics of MPs follow a first-order model, as illustrated in Equation 10.

$$rate = K_{bio} C_{ss} C_{dis} \tag{10}$$

where K_{bio} is the biodegradation rate constant, C_{ss} is the suspended solids concentration (g/L), and C_{dis} is the dissolved concentration of MPs_{ss} (g/L).

As a result, within the existing biological treatment processes implemented in municipal wastewater, around 90% of the MPs are neither removed or biotransformed (Das et al., 2017).

Future Work/Recommendations

The information researched above will be used for future work by two PhD students at École Nationale Supérieure des Industries Chimiques (ENSIC) in Nancy, France. Using the knowledge that was acquired, each PhD student will begin to conduct testing in a laboratory located at ENSIC to delve deeper into the hypotheses associated with hydrodynamics. The first student will look into finding the optimal reactor for wastewater treatment by modifying the hydrodynamics within the reactor and utilizing CFD modeling. The second student will experiment with bacteria in the wastewater and how turbulence and the use of baffles affects antibiotic resistance and the removal of micropollutants.

Future Work for Background 1

Finding the Optimal Reactor for Wastewater Treatment Using CFD

In this section, I will explore the need for future research in identifying the optimal reactor for wastewater treatment by manipulating hydrodynamics and utilizing the activated sludge process. This research is important because it helps meet the rising need for eco-friendly and efficient wastewater treatment methods. By focusing on this aspect, we can discover new ways to make treatment processes more effective while also reducing energy use and environmental harm. This work is vital for improving wastewater treatment and tackling urgent water quality and resource issues worldwide (Silva, 2023)

One prevalent recommendation I propose is to gather an array of reactor shapes featuring various baffles and sizes commonly utilized in benchtop scale laboratories. By doing so, we can identify the most efficient model from this assortment. Altering the shape, size, and internal configuration of the reactor significantly impacts the hydrodynamics of water flow within it. Determining the optimal design for wastewater treatment can give substantial savings in time, energy, and expenses for the operating plant. Utilizing computational fluid dynamics is essential for testing these reactors.

During my time at ENSIC, one of my initiatives was to start compiling a collection of different reactor examples I came across in research articles. I found approximately 40 examples, each with its own shape, size, and internal configuration. Figures 8 and 9 display two reactors I found that use activated sludge for treating wastewater.

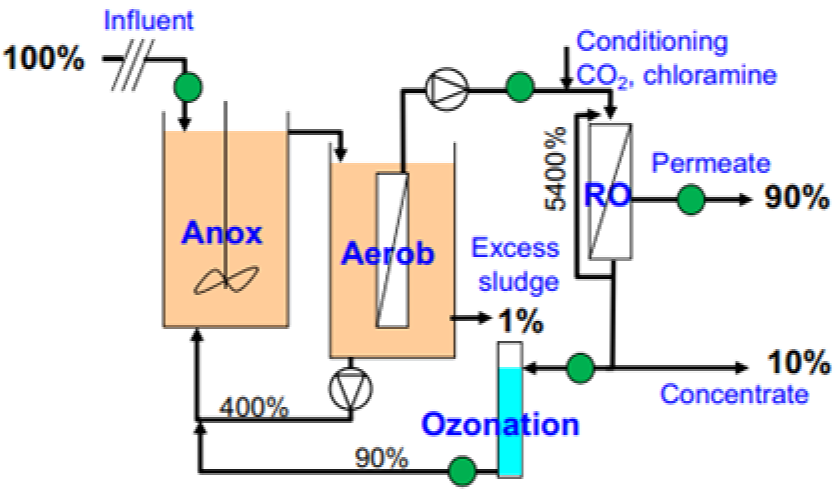

Figure 8. Schematic outline of experimental setup for the reactor utilized in Joss et al., 2011.

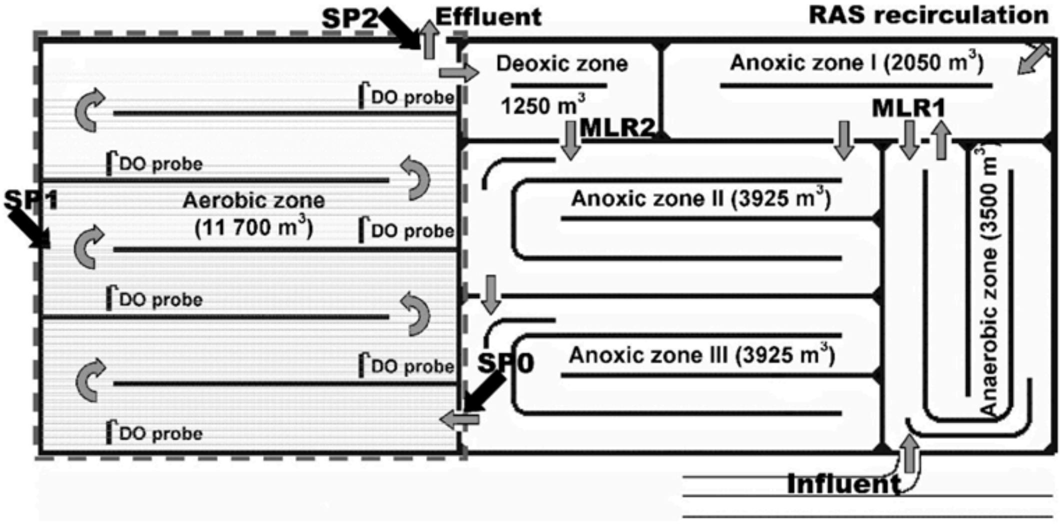

Figure 9. Schematic outline of experimental setup for the reactor utilized in Zima et al., 2009.

The most evident contrast between the two examples lies in their inner configurations and the distinct zones they feature. In Figure 8, there is a setup incorporating reverse osmosis and ozonation, whereas Figure 9 showcases multiple anoxic zones along with an extensive array of baffles designed to direct the flow of wastewater.

The CFD software is able to generate a detailed visualization of fluid behavior within each reactor, offering invaluable insights for this project. These visualizations provide insights into how the different inner configurations influence flow patterns, mixing efficiency, residence time distribution, and other critical hydrodynamic parameters.

By comparing the results obtained from testing reactors with varying inner configurations, we can identify which design optimally meets the requirements for specific applications, in this case, wastewater treatment. This analysis aids in optimizing reactor performance, improving efficiency, and reducing costs associated with operation and maintenance (Coker, 2001).

Future Work for Background 2

Combating Antibiotic-Resistant Bacteria

In this section, I will explore the need for future research on the efficacy of reactors in combating antibiotic-resistant bacteria. Understanding this aspect is crucial to prevent the transmission of such pathogens to humans, thereby safeguarding the well-being of the population.

Antibiotic resistance limits treatment options for bacterial infections, leading to increased illness, deaths, and healthcare costs. It also threatens standard medical procedures, strains healthcare systems, and imposes a significant global economic burden. Addressing this challenge requires collective efforts to promote responsible antibiotic use, develop new treatments, and prevent the spread of resistant bacteria, safeguarding public health (Dadgostar, 2019).

Considering the goal of improving public health, an essential future endeavor involves using the most efficient reactors to eliminate antibiotic-resistant bacteria. This entails examining the bacterial composition in municipal and industrial wastewater to identify prevalent antibiotic-resistant strains. By doing so, we can employ optimal reactors to remove these bacteria effectively. Such proactive measures will not only reduce the presence of antibiotic-resistant bacteria in wastewater but also contribute to maintaining the effectiveness of treatment options for bacterial infections, ultimately benefiting public health (World Health Organization, 2023).

Increasing Turbulence

In this section, I will explore the need for future research on increasing turbulence within the reactor to prompt mixing within the influent and create homogeneity.

Homogeneity in a reactor designed for bacterial removal is vital for ensuring uniform treatment conditions, consistent performance, optimized contact between bacteria and treatment agents, predictable outcomes, and resource efficiency. By maintaining uniformity throughout the reactor, all areas receive similar treatment, maximizing the efficiency of bacterial removal while minimizing the risk of regrowth or resistance development. Homogeneous reactors often require fewer resources, contributing to cost savings and environmental sustainability. Achieving homogeneity in such reactors is essential for safeguarding water quality and protecting public health (Gao et al., 2023).

Increasing turbulence enhances fluid movement and collision of particles, promoting thorough mixing and creating homogeneity in the reactor. Turbulent flow causes fluid particles to mix effectively, breaking down concentration gradients and ensuring uniform distribution of substances (Alberti et al., 2023).

Considering all these factors, increasing turbulence within a reactor can aid in the removal of antibiotic-resistant bacteria. To achieve this, various designs must be tested and evaluated to identify the most effective one. Figure 10 illustrates an example of a reactor featuring baffles designed to enhance turbulence in the influent. The sections colored in black represent fixed wall aspects, while the red sections depict suggested circular obstacles for testing. Although the baffles inside the reactor promote mixing at the outer layers of the influent, they may not adequately mix the fluid particles within the stream's interior. Therefore, introducing obstacles in the path around the bend ensures thorough mixing of all fluid particles.

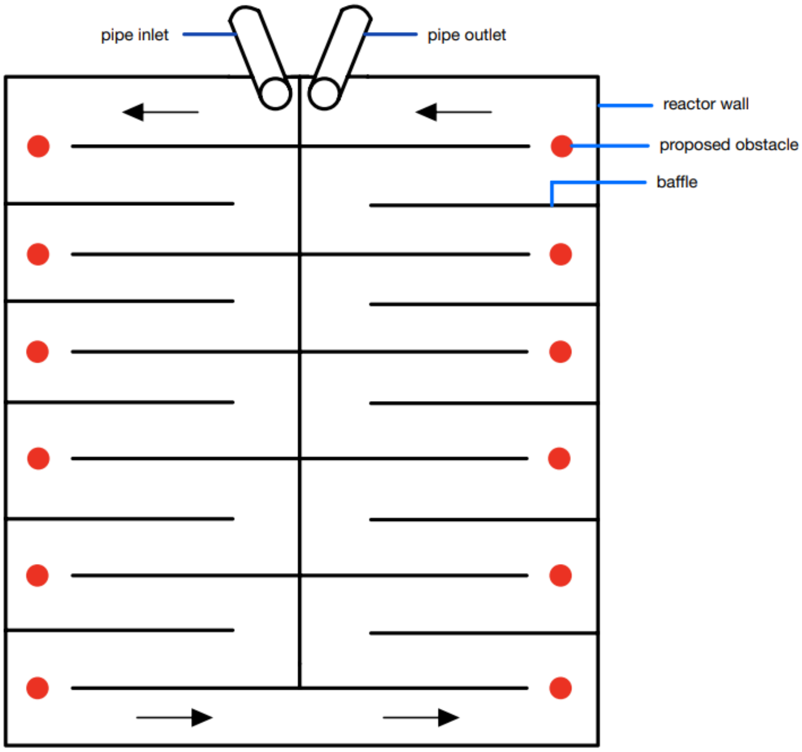

Figure 10. Original sketch illustrating the addition of circular obstacles to increase turbulence within the stream.

An alternative method to enhance turbulence involves adding a static mixer before the reactor, which promotes mixing in the stream prior to entering the reactor. An example of a static mixer can be pictured in Figure 11. The mixing elements within a static mixer disrupt the flow profile, ensuring thorough mixing to create a homogeneous mixture. A notable advantage of static mixers is their lack of moving parts, resulting in minimal maintenance requirements, low energy consumption, and absence of electrical components that could pose safety risks (Primix, 2024). Moreover, static mixers offer consistent mixing of materials, regardless of the operator, leading to reproducible mixing outcomes and high reliability (Schöck, 2023).

Figure 11. Static Mixer (Koflo Corporation, 2024).

Conclusion

Utilizing all the gathered research, two PhD students enrolled at École Nationale Supérieure des Industries Chimiques (ENSIC) in Nancy, France, are prepared to advance their research. Their primary focus revolves around innovating activated-sludge based reactor designs to optimize hydrodynamics, a complex task they intend to address through careful modeling of a wide range of computational fluid dynamics (CFD) simulations. Moreover, their research endeavors extend to confronting critical environmental challenges, including combating antibiotic-resistant bacteria and mitigating the presence of micropollutants. Through rigorous experimentation and the implementation of innovative methodologies, these PhD students aim to develop new methods that promote sustainable wastewater treatment practices, thus safeguarding public health and preserving ecological integrity for future generations.

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