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Impact of impeller rotational seed on sludge velocity distribution in a double helical ribbon reactor: A CFD-based study

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Abstract This study employs three-dimensional Computational Fluid Dynamics (CFD) simulations to evaluate the influence of impeller rotational speed on sludge velocity distribution, dead zone formation, and overall mixing behavior in a Double Helical Ribbon Impeller (DHRI) reactor. The investigation also explores the scale-up implications of DHRI configuration from laboratory to pilot scale (scale up). CFD simulations were performed using ANSYS Fluent 22R2, where the continuity and Navier-Stokes equations were solved using the finite volume method. A single-phase, non-Newtonian rheological model was applied to simulate high-solid anaerobic digestion sludge with a total solid concentration of 12%. Simulations were conducted for both a 10 L lab-scale reactor and a scaled-up (270 L) reactor at impeller speeds of 50, 100, and 150 rpm. The results indicate that increasing impeller rotational speed significantly enhances sludge distribution, leading to improved mixing efficiency and reduced formation of dead zones. At 50 rpm, 15% of the reactor volume remained poorly mixed, especially in the conical bottom zone. This was significantly reduced to less than 2% at 150 rpm. However, the most effective balance between mixing performance, shear stress, and energy consumption could be considered at 100 rpm. Beyond this threshold, further increasing the rotating speed of the impeller will have almost no effect on mixing performance but rather necessitates share stress and more energy consumption. The scale-up simulations demonstrated that the hydrodynamic mixing characteristics observed in the laboratory-scale DHRI reactor were largely preserved in the scale up (270 L) reactor. This consistency in flow dynamics across scales can be attributed to the application of geometric similarity and consistent sludge rheology, which might ensure comparable Reynolds numbers between the two configurations. These findings suggest that, unlike many conventional impeller systems which suffer from performance degradation upon scale-up, the DHRI reactor retains its superior mixing capability even at larger volumes. Moreover, the DHRI configuration showed clear advantages over conventional impeller designs reported in previous literature, particularly in handling high-solids substrates such as chicken manure slurry. Its unique geometry might had promoted strong axial and radial flow components, ensuring uniform sludge distribution throughout the reactor volume, indicating the tendency to minimize sedimentation or scum layer formation. This performance is crucial for enhancing mass transfer, maintaining microbial activity, and supporting stable and efficient biogas production in high-solids anaerobic digestion systems. Overall, this study contributes to the understanding of fluid flow and mixing dynamics in DHRI reactor, offering fundamental insights and practical design guidelines for effective scale-up. It underscores the importance of optimizing impeller speed not only for improved mixing but also for minimizing energy use and mechanical stress. The results affirm that DHRI reactor is a promising design for high-solids anaerobic digestion applications and presents a scalable mixing solution for industrial bioreactor configurations. Future research should incorporate experimental validation and extend investigations to assess the impact of mixing on microbial kinetics and methane yield under varying operational conditions like rpm.

Keywords: computational fluid dynamics, double helical ribbon impeller, high-solids anaerobic digestion, mixing optimization, non-newtonian rheology, scale-up effects

1. Introduction

Mixing is a critical process parameter in the design and operation of anaerobic digesters, particularly in high-solids systems, where inadequate mixing can lead to stratification, scum formation, and localized inhibition due to pH or temperature gradients (Zhou et al. 2019, Li et al. 2022, Agborambang et al. 2022). Efficient mixing enhances mass and heat transfer, ensures uniform distribution of substrates and microbial populations, prevents sedimentation and scum, thereby improving process stability and biogas yield (Singh et al. 2021, Wang et al. 2018). Among various mechanical mixed reactors, the double helical ribbon impeller (DHRI) reactor has emerged as a promising design for processing high solid (like chicken manure slurry), non-Newtonian sludge (Ahmadi et al. 2021, Wang et al. 2018) due to its superior axial mixing capabilities and low shear characteristics (Zhou et al. 2019, Singh et al. 2021). However, a detailed understanding of how impeller rotational speed influences the mixing behavior and sludge distribution in such systems remains underdeveloped.

Computational Fluid Dynamics (CFD) has become an indispensable tool for evaluating flow patterns and mixing dynamics in anaerobic digesters, offering insight into the hydrodynamic environment without the high costs and limitations of experimental setups (Ahmadi et al. 2021, Li et al. 2022). CFD has been extensively applied to study impeller configurations, mixing times, energy input, scale-up effect and their influence on anaerobic digestion efficiency (Singh et al. 2021, Agborambang et al. 2024). The CFD process typically follows three main stages: preprocessing, where geometry creation and mesh generation occur; processing, which involves defining physics models, numerical parameters, and running calculations until convergence; and post-processing, where results are visualized and analyzed to extract meaningful insights about digesters' hydrodynamic behavior (Fig. 1). Most previous studies have either focused on geometric optimization (Ahmadi et al. 2021) or limited speed analysis of DHRI reactor (Wang et al. 2018, Singh et al. 2021). There remains a lack of systematic studies that explore how varying the impeller rotational speed in a DHRI reactor influences the mixing pattern, sludge distribution, potential formation of dead zones and scale-up effect on mixing performance. Singh et al. (2021) explored the optimization of mixing regimes in anaerobic digesters using conventional helical ribbon impellers. Their study linked improved mixing to enhanced methane production and emphasized the role of impeller speed in preventing scum formation and sedimentation. However, their CFD analysis was limited to a single impeller speed, leaving open questions about how different rotational speeds may affect sludge homogenization and mixing energy requirements. Similarly, Zhou et al. (2019) addressed the importance of impeller speed and mixing energy in high-solids anaerobic digestion (HSAD) through a validated CFD study. Their study revealed that insufficient mixing at low speeds led to dead zones and reduced bioreactor efficiency, while excessively high speeds resulted in energy waste without proportional gains in biogas production. These findings underscore the need for a systematic analysis of the relationship between impeller rotational speed and sludge distribution, a gap this study aims to fill.

The current study addresses this research gap by conducting 3D CFD simulations, using a single-phase framework and implementing non-Newtonian rheology. This study aims to evaluate sludge distribution and characterize flow patterns at varying impeller rotational speeds, while also investigating the scale-up effects of DHRI reactor on sludge distribution.

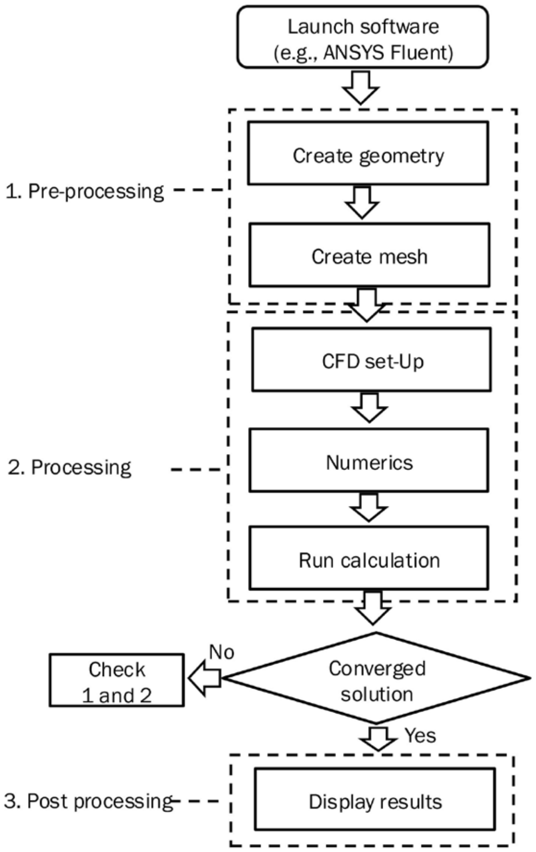

Fig 1. An overview of the procedural steps involved in the computational fluid dynamics (CFD) process.

2. Materials and Method

2.1. Reactor Geometry and Discretization

The DHRI reactor was designed and simulated by using ANSYS Workbench, version 22R2 (Agborambang et al. 2024). The schematic diagram of the reactor and impeller, along with their dimensions are shown in Fig. 2a and 2b respectively. The 3D geometry was designed using ANSYS SpaceClaim and the reactor had a working volume of 10 L. Fig. 3a and 3b shows the CFD model of DHRI reactor and impeller structure. The DHRI reactor consisted of two helical blades symmetrically wrapped around a central shaft (Fig. 3b). The bottom of the reactor had a conical shape to ease the removal of sediments like sand and was fully filled with sludge with total solid (TS) concentration of 12% (Wu 2012). The mesh statistics (cells, faces, nodes, quality, etc.) and meshed geometry are presented in Table 1 and Fig. 3c, respectively.

Table 1. Rheological properties of sludge*

Slurry type	Total solid (%)	Consistency index, K (Pa S^n)	Flow index, n	Share rate, $\dot{y}$ (S^{-1})	Density, ρ (Kg/m^3)
Sludge	12	2.4	0.38	0.8-23.9	1063.6

* Rheological properties of sludge was tested at T= 35ºC as reported by Wu (2012)

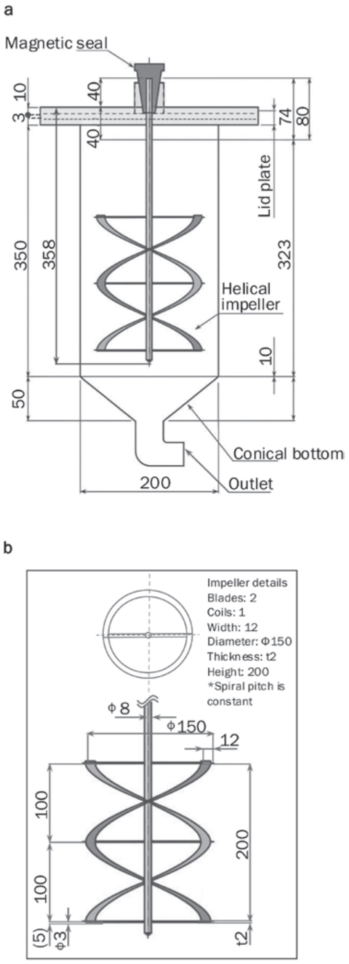

Fig 2. Dimensions of reactor (a) and impeller components (b) in millimeters (mm).

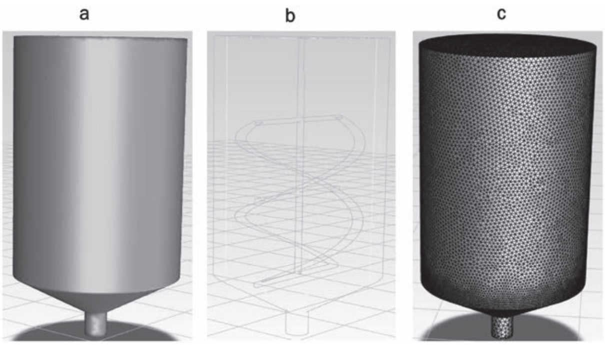

Figure 3. Geometry (a), impeller structure inside geometry (b) and meshed geometry (c).

2.2. Rheological model and definition of dimensionless numbers

This rheology was implemented using a User-Defined Function (UDF) in ANSYS Fluent, version 22R2 to ensure accurate simulation of the fluid behavior across the reactor domain. A mathematical model characterizing mechanical mixing for high solid anaerobic digestion (HSAD) requires differentiation between rheological properties of high-solids materials that exhibit dual liquid and solid behavior. For instance, sand-laden dairy manure has been demonstrated to act like a non-Newtonian liquid below 50% total solids (TS), whereas heavily bedded dairy manure exhibits solid properties at 25% TS (Salehiyon et al. 2015). The model formulated herein exclusively addresses high-solid materials that maintain liquid characteristics and is predicated upon the following assumptions. (1) The model is a single phase (to reduce the simulation complexity), and mixing in digesters is performed under turbulent flow conditions (2) The sludge is assumed to fill the entire DHRI reactor volume. (3) The digestion temperature is constant at 35oC and (4) Municipal solid waste and sludge exhibit non-Newtonian pseudo-plastic fluid behavior when TS is greater than 2.5% (Wu 2012). The rheology of the sludge used in this study is presented in Table 2. The apparent viscosity (η) and density (ρ) of manure slurry are expressed as (Landry et al. 2004, Wu & Chen

$$n = K\dot{y}^{n-1}e^{T_0/T} \quad (1)$$

$$\rho = 0.0367TS^3 - 2.38TS^2 + 14.6TS + 1000 \quad (2)$$

Table 2. Mesh Statistics of the geometry

Cell type	Total sells	Faces	Nodes	Cell size	skewness
Tetrahedral	543764	1136466	93795	0.006 m	0.23

2008):
where k is the consistency coefficient, ŷ the shear rate, n the power-law index, T0 the reference temperature, T the digestion temperature, and TS is the weight percentage of TS in the sludge.

For mechanical agitation of non-Newtonian fluids,

$$\dot{y} = K_s N \tag{3}$$

Metzner & Otto (1957) proposed a correlation as:
where N is the represents the impeller rotational speed, and Ks is a constant value that is dependent on impeller type. Ks = 23 for the helical ribbon impeller as recommended by Ihejirika & Ein-Mozaffari (2007).
Then the Reynolds number (Re) for mechanical agitation of non-Newtonian fluids can be calculated by (Chen

$$Re = \frac{\rho N d^2}{\eta} \tag{4}$$

1981):
where d^2 is the impeller diameter.

2.3. Numerical method and Boundary Condition

The CFD code was based on solving the continuity and the Navier-Stokes equations using a finite volume method. The transport equations are integrated over their own control volume using the hybrid scheme discretization method. Second-order upwind for momentum equations, PRESTO scheme for pressure and SIMPLE scheme for pressure-velocity coupling were selected. Residuals for continuity and momentum < 1e-4, and steady-state volume-averaged velocity profile stability were set for convergence criteria (Patankar et al. 1980). The algebraic equation solutions are obtained in reference to the fundamental study by Douglas et al. (1964). The discretization method and numerical solution procedure used have been described in detail elsewhere (Bouzgarrou et al. 2009). Non-slip boundary condition was applied at the vessel walls and bottom. Rotational motion was modeled using a rotating reference frame (MRF) approach with rotational speeds of 50, 100, and 150 rpm to examine their effect on sludge distribution. The top surface was treated as a symmetry plane. Pressure-based, transient, turbulent (K-epsilon (2 eqn)). Time step of 0.01 second was selected with a total simulation time of 20 seconds. A scale factor of 3 was applied to the lab-scale DHRI reactor (10 L) to scale-up

$$V' = Vk^3 \tag{5}$$

to 270 L by applying geometric scaling law.
Where V is the original volume, V′ is the scale-up volume and K is the scaling factor.
Dead zones were defined as regions with velocity magnitudes below 5% of the maximum velocity in the reactor (Sindall et al. 2013).

3. Results and Discussion

3.1. Effect of Impeller Rotational Speed on Velocity Distribution (Lab-scale)

Mixing efficiency was evaluated by tracking the distribution of the sludge zones of DHRI reactor. The velocity contour distributions at different impeller rotational speeds (50, 100, and 150 rpm) are presented in Fig. 4. The color scale represents the fluid velocity magnitude ranging from 0 to 9.63 $m\ s^{-1}$. A significant variation in flow patterns and velocity distributions was observed

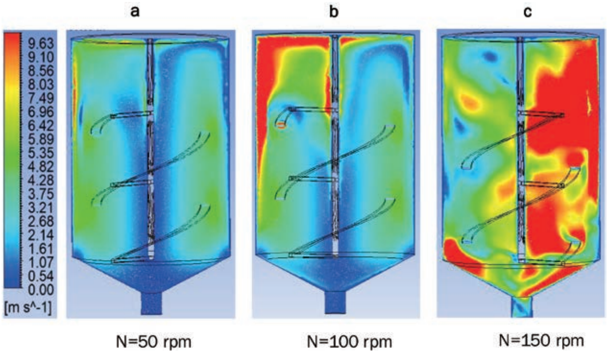

Figure 4. Velocity contours distribution at different impeller rotational speed: N=50 rpm (a), N=100 rpm (b) and N=150 rpm (c) in a lab-scale DHRI reactor. The color scale represents the fluid velocity magnitude (m s^{-1}).

with increasing rotational speeds. At 50 rpm (Fig. 4a), the velocity distribution exhibited a relatively uniform pattern with predominantly low-velocity regions (blue-green) throughout the reactor. The maximum velocity was observed near the impeller blades, but these higher velocity zones did not effectively distribute throughout the reactor volume. This observation aligns with findings by Zhou et al. (2019), who reported that low rotational speeds often fail to generate sufficient momentum for complete mixing in high-solids digesters. The conical bottom region displayed particularly low velocities, suggesting potential for solids accumulation and formation of dead zones, which can negatively impact digester performance (Li et al. 2022). At 100 rpm (Fig. 4b), a substantial increase in velocity magnitude was observed throughout the reactor, with more pronounced high-velocity regions (yellow-red) developing around the impeller and extending further into the bulk fluid. This enhanced momentum transfer led to improved circulation patterns, consistent with observations by Singh et al. (2021), who found that moderate rotational speeds significantly improve sludge homogenization. The helical ribbon design demonstrated its effectiveness by creating both axial and radial flow components, contributing to the reduction of dead zones particularly in the central reactor region. At 150 rpm (Fig. 4c), the velocity distribution revealed intense mixing with high-velocity regions (red) dominating the upper portion of the reactor and extending deeper into the reactor. The fluid dynamics at this speed showed complex flow patterns with strong recirculation zones. This observation is consistent with that of Ahmadi et al. (2021), who reported that at higher rotational speeds, helical ribbon impellers generate robust axial pumping action that enhances the overall mixing efficiency. However, velocity gradients became more pronounced, with localized high-velocity regions potentially creating excessive shear forces that could be detrimental to sensitive microbial communities (Singh et al. 2021, Agborambang et al. 2024).

3.2. Dead Zone Formation

Dead zones, defined as regions with velocity magnitudes below 5% of the maximum velocity (Sindall et al. 2013), were quantified for each rotational speed. At 50 rpm, dead zones occupied approximately 15% of the reactor volume, primarily concentrated in the conical bottom region and along the impeller shaft. This observation aligns with findings from Li et al. (2022), who reported that low mixing intensities fail to mobilize and uniformly distribute high-concentration slurries. At 100 rpm, dead zones decreased significantly to approximately 9% of reactor volume, while at 150 rpm, they were further reduced to less than 2%. The DHRI reactor configuration demonstrated superior performance compared to conventional impeller designs, as reported in literature. Singh et al. (2021) investigated the effect of mixing intensity on biogas production in a lab-scale single helical ribbon impeller reactor (conventional type) using a CFD approach, with sewage sludge having a low TS concentration of 4.3% (low-solid). They reported the maximum velocity at 67 rpm was recorded as 0.5 ms^{-1} which implies that slightly increasing the sludge TS concentration above 4.3% could result in significant dead zones. While our results on DHRI reactor, with high sludge TS concentration (12%), showed a considerably higher maximum of 9.6 ms^{-1} velocity at 100 rpm. This performance advantage can be attributed to the unique geometry of the DHRI reactor, which creates efficient top-to-bottom circulation patterns essential for processing high-solids substrates (Singh et al. 2021). This study mainly focuses on CFD simulation approach, future studies on validation of CFD results with experimental data could be helpful to verify the efficiency of CFD simulation.

3.3. Effect of Scale-up on Flow Dynamics and Practical implication

The effect of TWF-CDD scale-up on sludge velocity distribution was investigated in this study by applying CFD simulation. The lab-scale DHRI reactor (10 L) was scale-up to 270 L, with a scale factor of 3 applied following geometric scaling law (equation 5). The same geometric configuration, rotational speed (50, 10, and 150 rpm), sludge rheology, boundary and operating conditions were similar to the lab-scale model. Based on the simulation results, the velocity contour distributions, flow pattern and dead zones in the scaled-up DHRI reactor with geometric and impeller rotational speeds (50, 100, and 150 rpm) similarities are illustrated in Fig. 5. Comparison between Fig. 4 and 5 reveals no significant differences in flow patterns and velocity distributions between the lab-scale and scaled-up DHRI reactor. The similarity in velocity sludge velocity distribution between the lab-scale and scale-up DHRI reactor may be attributed to comparable geometric configurations, rotational speed and sludge rheology, which help maintain a consistent Re across both scales (Agborambang et al. 2024).

These findings are consistent with the study by Hu et al. (2022), who conducted a comprehensive study on the scale-up effects of stirred tank reactors (excluding DHRI reactor) in (HSAD), examining both pilot-scale (14.4 m^3) and full-scale (3888 m^3) configurations. Their investigation employed CFD simulations alongside experimental measurements to assess the hydrodynamic characteristics of the digesters, with a particular focus on the influence of generalized Re and rotational speed. The study concluded that, among geometrically similar reactors, maintaining Re similarity offers greater relevance for scale-up considerations than matching rotational speeds.

The scale-up analysis has significant implications for industrial applications of DHRI reactors in high-solids anaerobic digestion. The results demonstrated that simple geometric scaling with similarities in sludge rheology, rotational speed and operational parameters can maintain the mixing performance in a larger scale reactor. This finding is particularly critical for processing high-solids substrates like chicken manure slurry, where adequate mixing can severely impact process stability and biogas yield (Wang et al. 2018). For industrial implementation, the study recommends employing geometric and sludge rheology (Reynolds number)

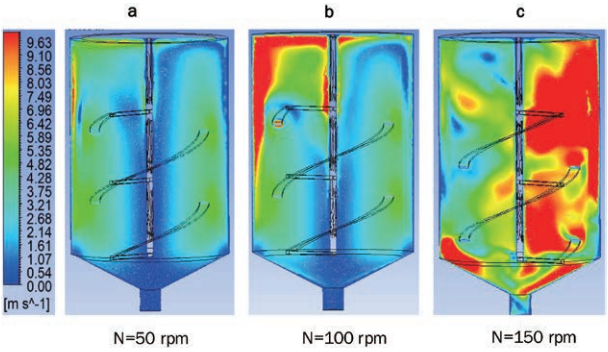

Figure 5. Velocity contours distribution at different impeller rotational speed after scale-up: N=50 rpm (a), N=100 rpm (b) and N=150 rpm (c) in a scale-up DHRI reactor. The color scale represents the fluid velocity magnitude (m s^{-1}).

scaling criterion with computational validation to determine appropriate mixing performance of DHRI reactor. Additionally, the power consumption analysis should be considered to determine the economically viable balance between mixing efficiency and energy expenditure. Overall, the study also revealed that DHRI reactor configurations (lab-scale and scale-up) retain their superior mixing capabilities during scale-up compared to conventional impeller designs. Li et al. (2022) reported that standard impellers suffer from dramatic reduction in mixing efficiency during scale-up, while our results demonstrated that DHRI reactor designs maintain relatively consistent performance across scales, at all rotational speeds tested in this study (50, 100, and 150 rpm).

4. Conclusions

This CFD-based study on sludge mixing in DHRI reactors has provided valuable insights into the effects of impeller rotational speed on mixing behavior and the implications of scale-up on flow dynamics. The key findings can be summarized as follows: (1) Impeller rotational speed significantly influenced velocity distribution and dead zone formation in the DHRI reactor. Optimal mixing performance was achieved at 100 rpm, which provided the best balance between mixing performance, share stress and power preservation, (2) The DHRI reactor configuration demonstrated superior performance compared to conventional impeller designs reported in literature, with significantly reduced dead zones and improved axial circulation essential for processing high-solids substrates, and (3) Simple geometric scaling with similarities in sludge rheology, rotational speed and operational parameters can maintain consistent mixing performance between laboratory and larger scales. These findings contribute to the fundamental understanding of mixing dynamics in HSAD and provide practical guidelines for the design and operation of DHRI reactor across different scales (lab-scale = 10 L and scale-up = 270 L). Future research should focus on experimental validation of these computational findings and investigation of the effects of mixing patterns on biogas production and process stability.

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