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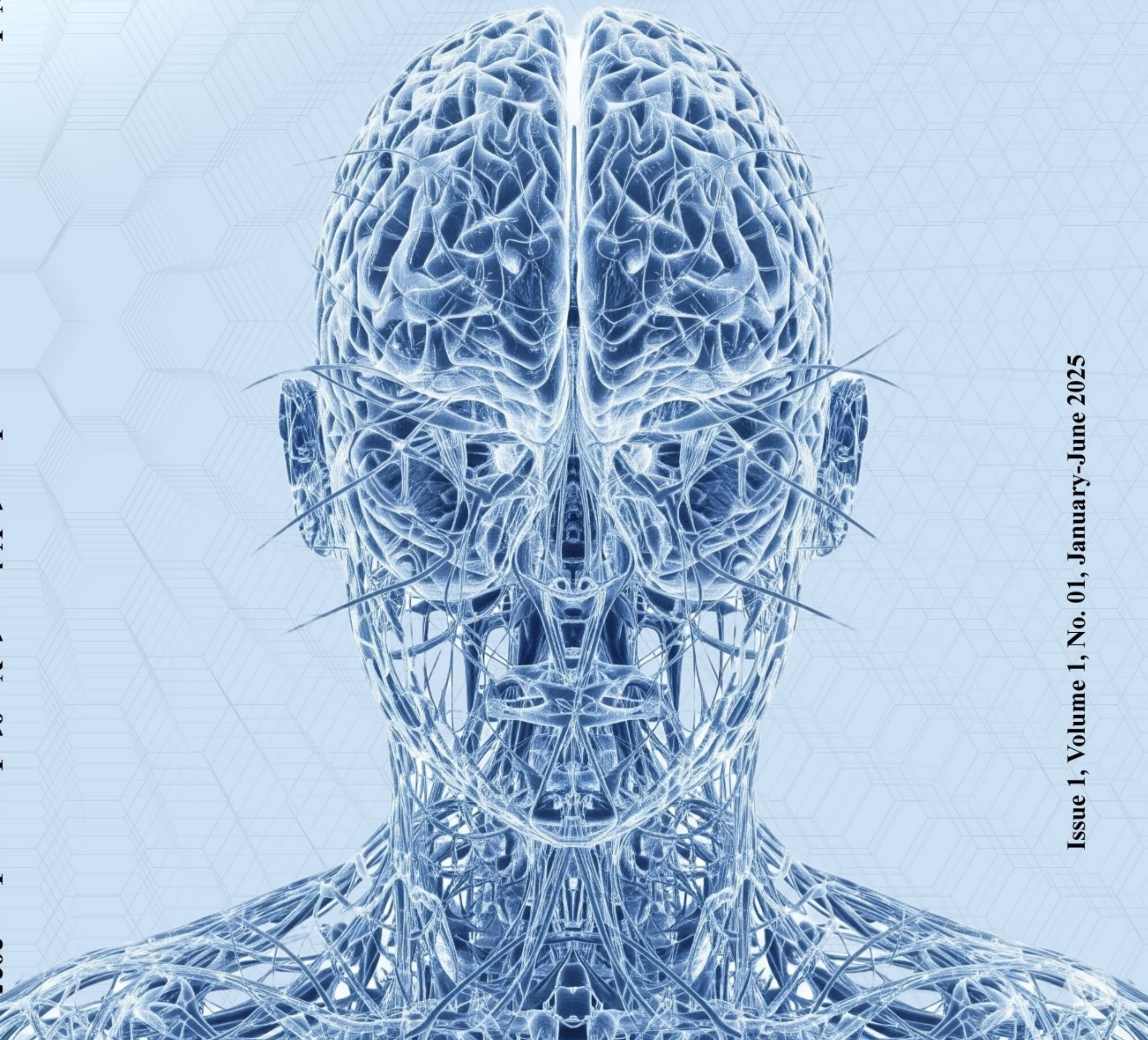

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Validation of Paste Mixing for Pouring Operations in the Ceramic Sector Using CFD Simulations in SolidWorks

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***PhD. Alfredo Gutiérrez García**
Universidad Tecnológica del Norte de Guanajuato
alfredo.gutierrez@utng.edu.mx
https://orcid.org/0000-0002-8197-8144

Eng. Gabriel Ángel Aguilar Bárcenas
Universidad Tecnológica del Norte de Guanajuato
gabriel.aguilar@utng.edu.mx
https://orcid.org/0009-0008-3618-8822

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*** Corresponding Author:** alfredo.gutierrez@utng.edu.mx

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ABSTRACT

This study aims to determine the optimal parameters for preparing ceramic slip intended for casting in gypsum molds, with the goal of improving its rheological properties (density, viscosity, flowability) and enhancing the quality of the final product. Key variables were evaluated, including water volume, mixer rotation speed (RPM), number and arrangement of blades, mixing time, and resting time.
The methodology was based on a fractional factorial design 2^{7-3} (1/8 fraction) with 16 experimental runs, allowing the analysis of both individual and combined effects of the variables. Data were collected through measurements of viscosity (using a Ford Cup No. 4), density, flowability, and paste homogeneity. Statistical tools such as ANOVA and response optimization graphs (using Minitab) were employed for data analysis.
Results showed that increasing the water volume to 152 liters and raising the mixer speed to 350 RPM favored better particle dispersion and homogenization. Increasing the number of blades to 6, evenly spaced, improved the distribution of mixing energy. Reducing the mixing time to 1 hour lowered energy consumption and helped prevent air entrapment. An extended resting period of 8 hours proved essential for stabilizing the paste and enhancing its fluidity. The ideal density achieved was 1.9625 kg/L, with an average viscosity of 266 centistokes.
Although the statistical analysis indicated that not all variables were significant at a 95% confidence level, a useful predictive model was obtained with a coefficient of variation of 100%, indicating high consistency among the data. Therefore, this model can be confidently used to optimize the ceramic slip mixing process, enabling more efficient and higher-quality production in both artisanal and industrial settings.

KEYWORDS

Computational fluid dynamics; Fluid dynamics; Manufacturing processes; 3-D modelling; Simulation; Computer simulation.

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INTRODUCTION

The preparation of ceramic slip for casting is a fundamental process in the ceramics industry, as the final product's quality largely depends on its proper formulation and mixing. This process involves creating an aqueous suspension primarily composed of plastic clays, fluxing agents such as feldspars, and debonding agents or anti-plasticizers, which help control plasticity and prevent deformations during drying and firing. Additionally, deflocculating additives such as sodium silicate, Sodax, polyphosphates, and organic acids are used to improve the dispersion of solid particles, reduce viscosity, and enhance the flowability of the mixture. These factors not only influence the physical properties of the finished product but also the efficiency of the production process.

From a scientific and technological perspective, ceramic slip preparation presents a challenge in industrial process optimization, as it involves complex variables such as density, viscosity, mixing time, particle size, resting time, and moisture level. Inadequate control of these variables can result in defects such as cracks, irregular porosity, difficulties in drying, and poor mold definition. From a social perspective, this type of research helps support artisanal workshops and small ceramic industries by improving their competitiveness and sustainability through more efficient and standardized techniques.

The central issue addressed in this study is the lack of a standardized protocol for preparing ceramic slip in artisanal workshops and small businesses, which can lead to inconsistencies in the final product's quality and unnecessary waste of materials and resources. Currently, many processes rely on empirical criteria or traditional practices that do not ensure optimal rheological properties of the slip. For example, improper dosing of water and deflocculants, excessively long mixing times without technical justification, and incorrect selection of mixer parameters such as rotation speed and number of blades are frequently observed, all of which affect both homogenization and suspension stability.

This study aims to establish a set of control parameters to optimize the ceramic slip mixing process for casting. It focuses on specific modifications to variables such as water volume, mixer speed, number of blades, and mixing time. These adjustments are intended to improve the slip's fluidity, reduce its viscosity, facilitate handling during molding, and minimize the risk of structural defects in the final product. The relevance of this research lies in its potential for direct application in local ceramic workshops, particularly in regions like Dolores Hidalgo, Guanajuato, Mexico, where ceramic production is deeply rooted in both culture and the local economy. The results indicate that these technical adjustments can lead to a significant improvement in product quality, as well as cost savings in energy and raw materials, contributing to the sustainable development of the artisanal ceramic sector.

DEVELOPMENT

A ceramic slip is an aqueous suspension composed of plastic clay, debonding agents or anti-plasticizers, and fluxes such as feldspars, each fulfilling a specific function: the clay provides plasticity, the debonding agents reduce shrinkage and prevent cracking during drying, while the fluxes facilitate vitrification by lowering the temperature required to achieve the desired density and porosity [1]. There are two main types of ceramic slip: hard porcelain and soft porcelain. The former is known for its high strength and requires firing at high temperatures, whereas the latter offers lower mechanical resistance and is fired at lower temperatures [2]. This classification is important in defining the type of final product, such as tableware, sanitaryware, or decorative pieces.

To ensure proper flowability the ability of the slip to completely fill the mold it is essential to strictly control the mixture's rheological properties. Among the main variables to consider are density, viscosity, mixing time, sieving, resting time, and the use of deflocculants [3]. Currently, the apparent density of the slip used is 1.9625 kg/L. Viscosity is directly influenced by the amount of water and the use of deflocculants such as sodium silicate, Sodax, polyphosphates, and organic acids. These additives help disperse solid particles, allowing for a reduced water content without compromising fluidity. The typical mixing time is 2 hours, although it is recommended to sieve the slip through meshes to remove coarse particles. In addition, resting time contributes to improved product quality and reduces the risk of deformations or explosions during firing.

An important point is the relationship between viscosity and water content. By using efficient deflocculants, the water content can be reduced without affecting flowability, enabling faster drying and a lower risk of deformation. However, if too much deflocculant is added, the slip may become "gelled," where viscosity unexpectedly increases due to over-deflocculation [4]. On the other hand, the mechanical conditions of the mixer are also crucial. Currently, a 1 HP mixer with 3 blades of 20 cm in diameter is used at a speed of 350 rpm. It is important to simulate different mixing scenarios by systematically varying each parameter and evaluating its impact on density, viscosity, flowability, and slip stability.

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This simulation will be conducted under controlled and repeatable conditions in order to identify the optimal combination of variables that enables the production of high-quality ceramic slip using minimal resources.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

General Objective

To validate, through computational fluid dynamics (CFD) simulations in SolidWorks, the optimal mixing parameters of ceramic slip for casting operations identified in the first part of the study. This validation aims to verify their impact on homogeneity, viscosity, and flowability of the mixture, thereby optimizing the process from a numerical and technological perspective.

Specific Objectives

1. To develop a 3D model of the ceramic slip mixing system in SolidWorks, including the tank, mixer, and blades, using the geometric and mechanical configurations reported in the experimental study (number of blades, RPM, mixing volume, among others).
2. To simulate different mixing scenarios by varying parameters such as rotational speed, number of blades, and mixing time, in order to compare the results for viscosity, density, and flow distribution with those obtained experimentally in the first phase of the study.
3. To evaluate the predictive capability of the CFD model by analyzing errors between simulated and experimental results, with the aim of validating the proposed mathematical model and establishing its applicability in real-world production environments in both artisanal and industrial ceramic sectors.

OBJECT OF STUDY

The focus of this research is the validation of the ceramic slip mixing process intended for casting operations, using computational fluid dynamics (CFD) simulations in *SolidWorks Flow Simulation* software. This analysis aims to verify the optimal parameters identified in the first part of the study, such as water content, mixer rotational speed (RPM), number and configuration of mixer blades, and mixing time.

The objective is to evaluate how these variables influence the rheological properties of the slip viscosity, density, flowability, and homogeneity in order to validate the previously developed mathematical model and optimize the mixer system design from a numerical and technological perspective.

This study falls within the field of ceramic process engineering and has direct application in both artisanal and industrial sectors that require efficient and standardized ceramic slip preparation. CFD simulation allows for the visualization of flow patterns, dead zones, mixing energy distribution, and homogeneous particle dispersion factors that are not always observable through conventional experimental methods.

Therefore, the scope of this research encompasses not only the physicochemical behavior of the ceramic slip but also the numerical validation of a mixing model that can be applied in real production environments. This approach contributes to improving the final product’s quality, reducing energy costs, and minimizing material waste in the production process.

METHODOLOGY

Validating the ceramic slip mixing process for casting operations represents a fundamental step in ensuring the final product's quality, optimizing resource use, and standardizing production processes particularly in small scale artisanal and industrial settings. To achieve this objective, a structured methodology consisting of five key steps is employed:

1. Definition of the 3D Geometric Model
2. Simulation Domain Setup
3. Mesh Generation and Sensitivity Study
4. Simulation of Different Scenarios
5. CFD Model Validation as outlined below:

1. Definition of the 3D Geometric Model

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The first step involves the precise creation of the three-dimensional model of the mixing system, including the tank, mixer blades, and the space occupied by the ceramic slip. This model is developed using *SolidWorks*, a widely used software in engineering for mechanical design and process analysis. The importance of this step lies in the fact that a well-defined geometric model serves as the foundation for any CFD simulation, as it determines the physical representation of the real system. Additionally, it allows for the inclusion of details such as blade configuration (e.g., 3 or 6 evenly spaced blades), their size, tank shape, and other elements that influence flow behavior.

2. Simulation Domain Setup

Once the geometry is defined, the simulation domain i.e., the physical space where the fluid flow will occur must be established. This step includes defining initial and boundary conditions, such as mixer rotational speed (RPM), volume of slip, fluid density and viscosity, and surface properties (walls, blades). Proper domain setup is essential to ensure that the simulation accurately reflects the real mixing process. For instance, if an incorrect rotational speed is set or the rheological behavior of the slip is ignored, the simulation results may not represent the experimental process.

3. Mesh Generation and Sensitivity Study

Generating a high-quality numerical mesh is a critical step in any CFD analysis. The mesh divides the domain into small elements where the Navier-Stokes equations describing fluid motion will be solved. Mesh density, refinement in critical zones (such as near the blades), and element quality directly affect the accuracy of the results. This mesh sensitivity study will help identify the optimal mesh density that balances accuracy and computational time. This step is crucial to ensure that results are not numerical artifacts but rather representative of the actual physical behavior of the system.

4. Simulation of Different Scenarios

With the geometric model, domain, and mesh defined, simulations are carried out under various operational conditions. These conditions are based on the experimental parameters obtained in the first part of the study [5]. such as water content, RPM, number of blades, and mixing time. Simulating different scenarios allows for a comparison of how these variables affect flow, homogeneity, viscosity, and the presence of dead zones or trapped air. This step is key to exploring variable combinations that are not easily assessable through experimental methods alone, such as internal slip behavior or real-time velocity profiles.

5. CFD Model Validation

Finally, the CFD model is compared with the previously obtained experimental results [5]. This validation involves evaluating parameters such as simulated vs. measured viscosity, density, flowability, and spatial distribution of the mixture. If the results match within an acceptable error margin, the model can be considered validated and useful for predicting system behavior under new conditions. This step not only confirms the model's utility but also allows for the identification of potential improvements in mixer design or operational parameters.

Together, these five steps form a robust and systematic methodology for validating the mathematical model of the ceramic slip mixing process using CFD simulations in *SolidWorks*. Its implementation not only verifies experimental results but also enables optimization of the mixer design, reduces trial-and-error costs, and establishes a standardized protocol applicable to artisanal and industrial ceramic workshops. Moreover, the use of CAD/CAE tools such as *SolidWorks* reinforces the technological relevance of the study, positioning it as an example of digital engineering applied to traditional processes.

PHASES OF DEVELOPMENT

1. Definition of the 3D Geometric Model

Figure 1.

Dimensions to make the model in Solidworks.

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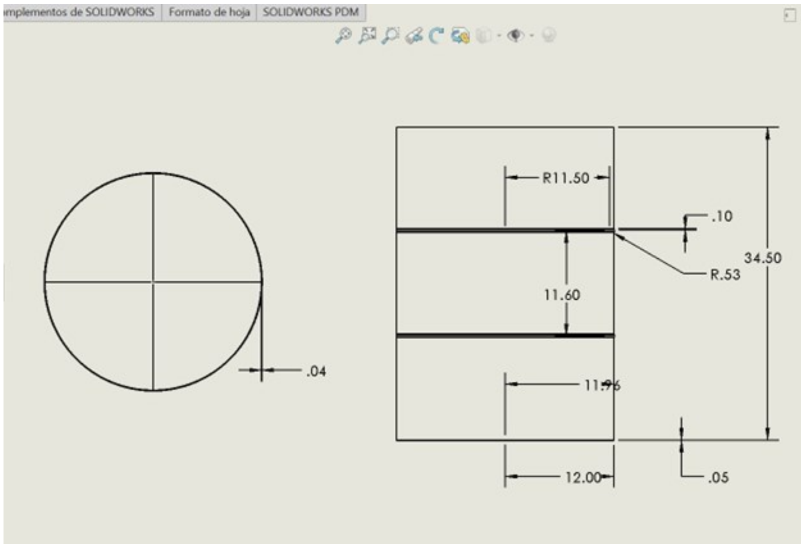
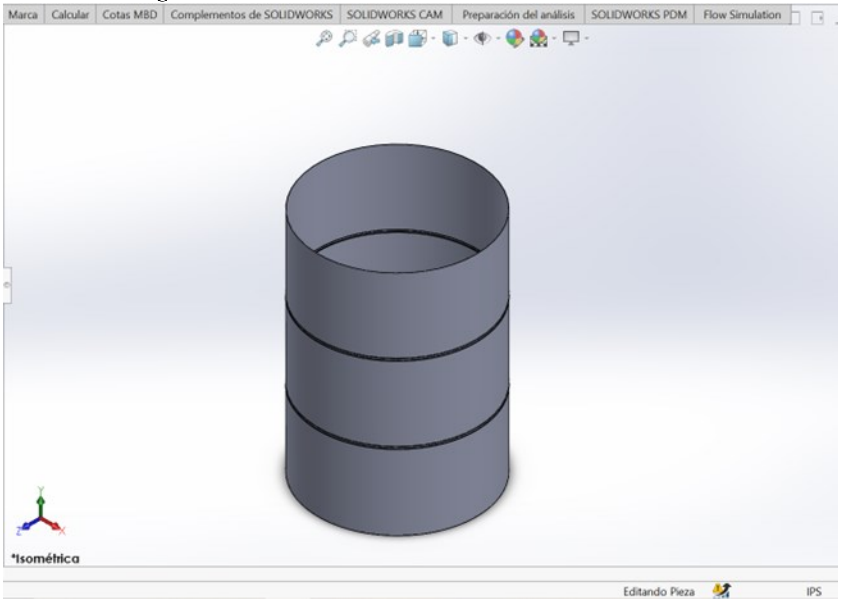


Note: Dimensions for creating a 3D model in Solidworks are shown. Source: https://es.uline.mx/Product/Detail/S-10759/Drums/Steel-Drum-55-Gallon-Closed-Top-Unlined-Black

Figure 2.
3D model design in Solidworks.



Note: The design of the model container used for paste testing is shown. Source: prepared by the authors.

Table 1.
Material properties AISI 1020 cold-rolled steel.

Abbreviation	Property	Worth	Unit
EX	Elastic modulus	2090405.5	kgf /cm^2
NUXY	Poisson's ratio	0.29	N/A
GXY	Shear modulus	815768	kgf /cm^2
DENS	Mass density	0.00787	kg/cm^3
SIGXT	Traction limit	4282.782	kgf /cm^2
SIGXC	Compression limit		kgf /cm^2

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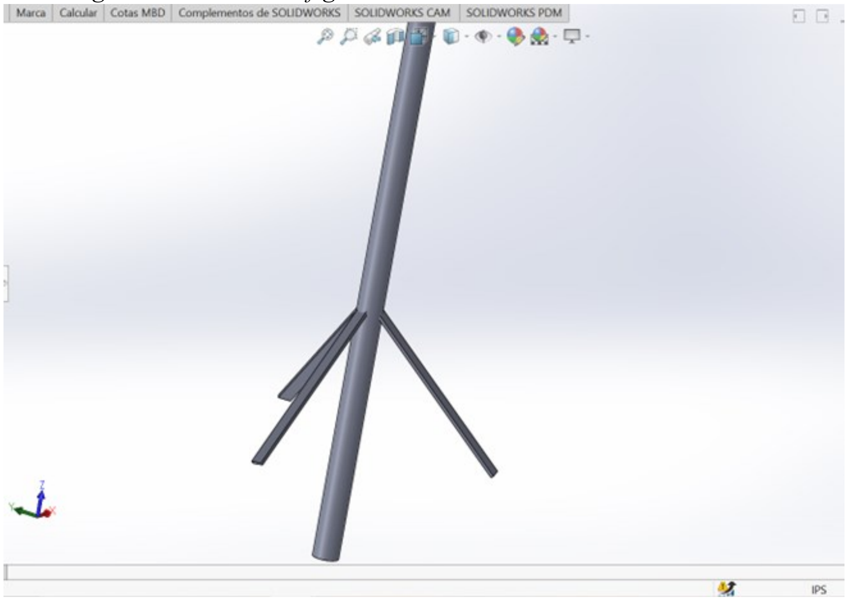
SIGYLD	Elastic limit	3568.985	kgf /cm^2
ALPX	Coefficient of thermal expansion	1.17E-05	/ ºC
KX	Thermal conductivity	0.124044	cal/(cm s · ºC)
C	Specific heat	116.157	cal/(kg·ºC)
MDAMP	Damping ratio of the material		N/A

Note: The physical and mechanical properties of the material used to make the model in Figure 2 are shown. Source: Solidworks database.

Figure 3.

Bar design and 3 shaker configuration.



Note: The design of the SolidWorks bar with three agitators used for mixing the ceramic paste is shown. Source: prepared by the authors.

Figure 4.

Bar design and 6 shaker configuration.

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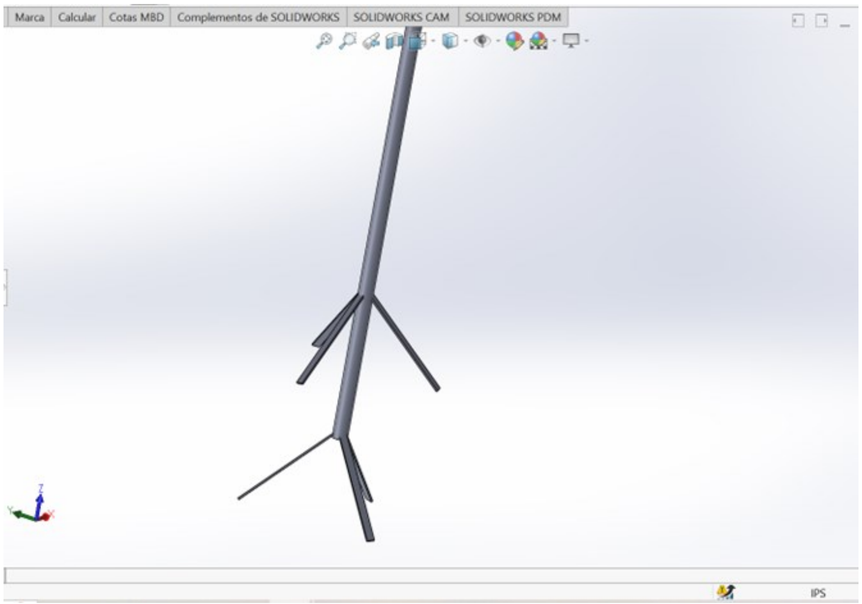

Note: The design of the Solidworks bar with six agitators used for mixing the ceramic paste is shown. Source: prepared by the authors.

Table 2.
Annealed stainless steel material properties.

Property	Worth	Unit
Elastic modulus	1968040.273	kgf /cm^2
Poisson's ratio	0.3	N/A
Traction limit	5608.405017	kgf /cm^2
Elastic limit	1406.130592	kgf /cm^2
Tangent module		kgf /cm^2
Coefficient of thermal expansion	1.60E-05	/ ºC
Mass density	0.008	kg/cm^3
Hardening factor	0.85	N/A

Note: The physical and mechanical properties of the material used to make the model in Figures 3 and 4 are shown. Source: Solidworks database.

2. Simulation Domain Setup

Once the 3D model was created in Solidworks, the study was prepared for subsequent simulation. The corresponding configuration is shown below.

Figure 5.
Model configuration/analysis types.

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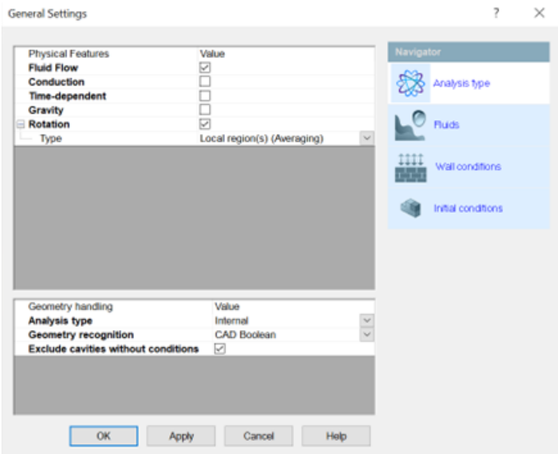
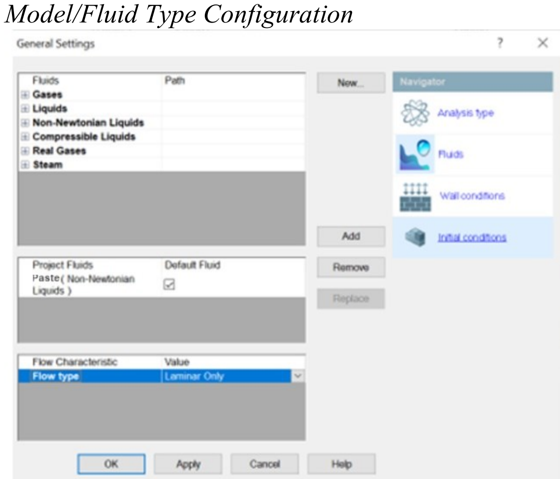


Note: The settings for preparing a CFD study are shown, where an internal fluid study has been performed. Source: Solidworks CFD study settings.

Figure 6.

Model/Fluid Type Configuration



Note: The settings for preparing the CFD study are shown, in which a non-Newtonian fluid was used due to the nature of the ceramic paste. Source: Solidworks CFD study settings.

Table 3.

Physical properties of ceramic paste.

Property	Typical value (approximate)	Units
Name	Ceramic paste	—
Density	1800–2200	kg/m^3
Specific heat	800–1200	J/(kg·K)
Thermal conductivity	0.5–1.5	W/(m·K)
Viscosity model	Power law	—
Consistency coefficient (K)	10–100	Pa·s
Power law index (n)	0.2–0.6	—
Maximum dynamic viscosity	~100	Pa·s
Minimum dynamic viscosity	~5	Pa·s

Note: The physical properties of the ceramic paste are shown; these data are approximate since they are strongly dependent on the specific formulation (percentage of water, type of clay, additives).

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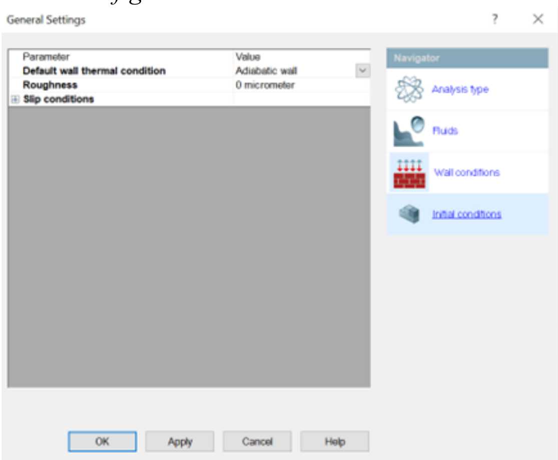
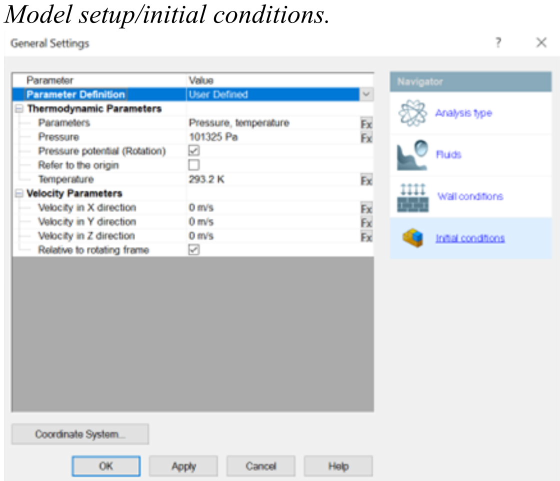
Figure 7.
Model configuration/wall conditions.



Note: The configuration for preparing the CFD study is shown, in this case, because the container has a coating to prevent the accumulation of material on its walls. Source: Solidworks CFD study configuration and https://es.uline.mx/Product/Detail/S-10759/Drums/Steel-Drum-55-Gallon-Closed-Top-Unlined-Black

Figure 8.
Model setup/initial conditions.

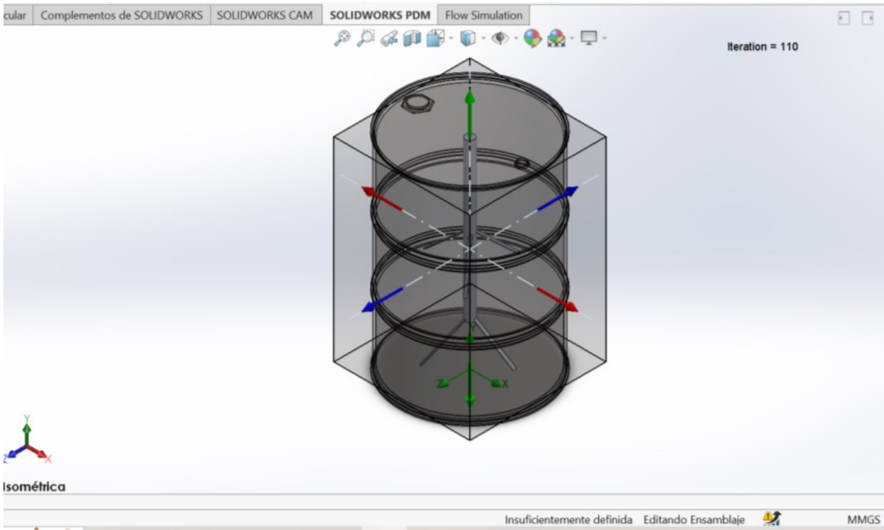


Note: The settings for preparing the CFD study are shown. Source: Solidworks CFD study settings.

3. Mesh Generation and Sensitivity Study

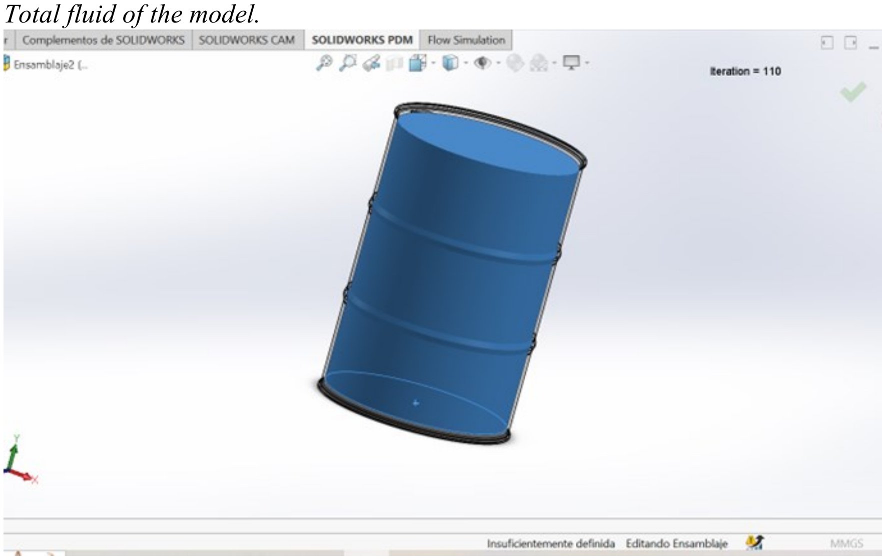
In the present stage of the study configuration, the configuration of the elements of the computational domain, the forces that will represent the ceramic paste and its behavior, in addition to the corresponding meshing have been carried out in order to carry out the corresponding simulation in the next stage, within which the following figures are shown:

Figure 9.
Representation of the computational domain.



CFD study is shown, where the top cover has been created in the 3D model to allow for the corresponding simulation. Source: Solidworks CFD study configuration.

Figure 10.
Total fluid of the model.



Note: The fluid to be simulated is shown, which consists of 0.216462 m^3. Source: Solidworks CFD study settings.

Figure 11.
Region that will exert the rotational force.

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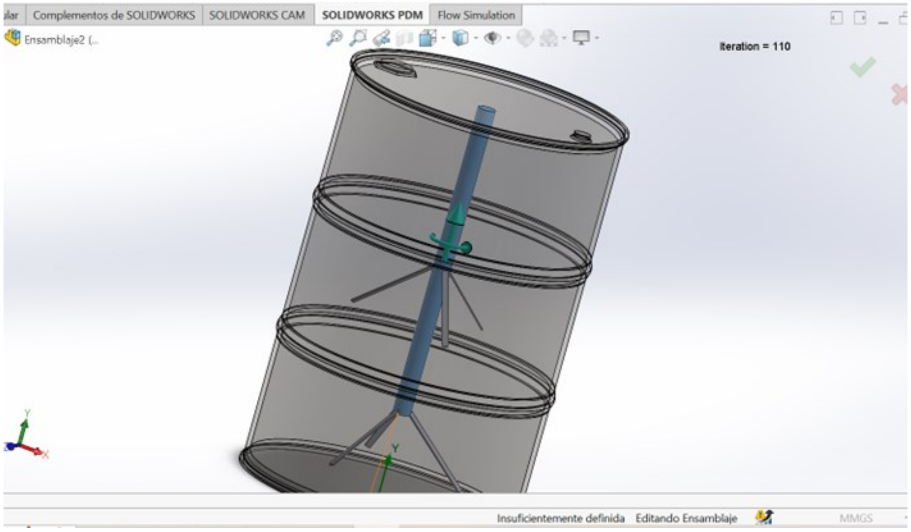
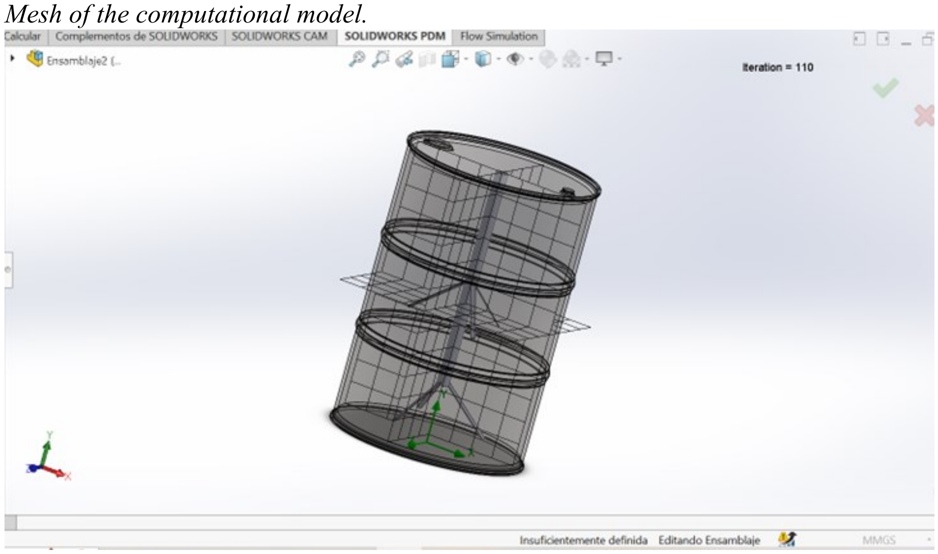


Note: The rotation region is shown, which will be implemented on the steel bar and the corresponding stirrers, which have been rotated counterclockwise and from bottom to top. Source: Solidworks CFD study configuration.

Figure 12.
Mesh of the computational model.



Note: The mesh used in the computational model is shown, which uses level 3 automatic meshing. This is due to the nature of the 3D model, which does not have many small curvatures. A minimum separation value of 0.58617 m between components is used. If the components have this value or less, they will be considered as a single solid in the simulation. Source: Solidworks CFD study configuration.

4. Simulation of Different Scenarios

For the next step, and to simulate different scenarios, two variations of the 3D model were used: one with three agitators and one with six. The simulation results show very significant differences between using one model and the other, as shown below.

Figure 13.
Simulation result.

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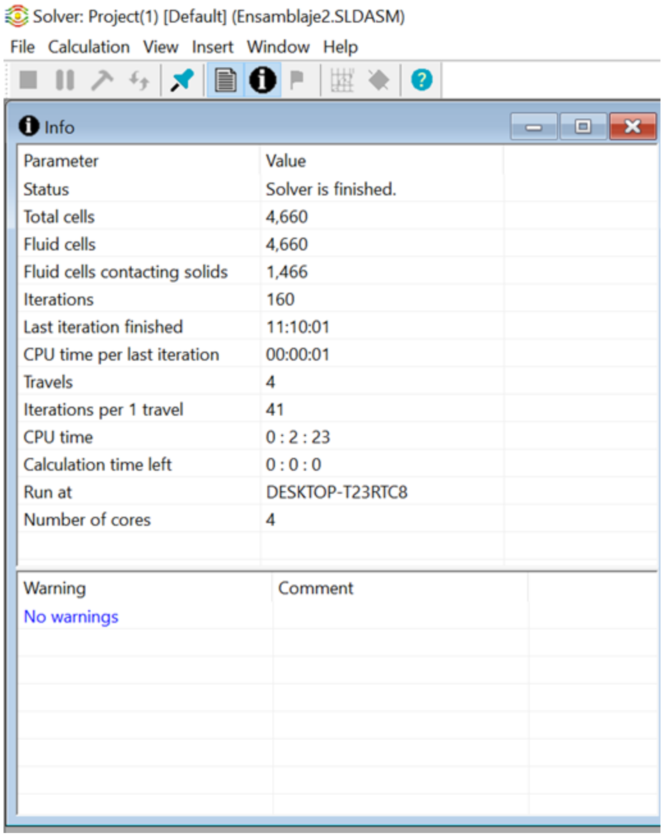
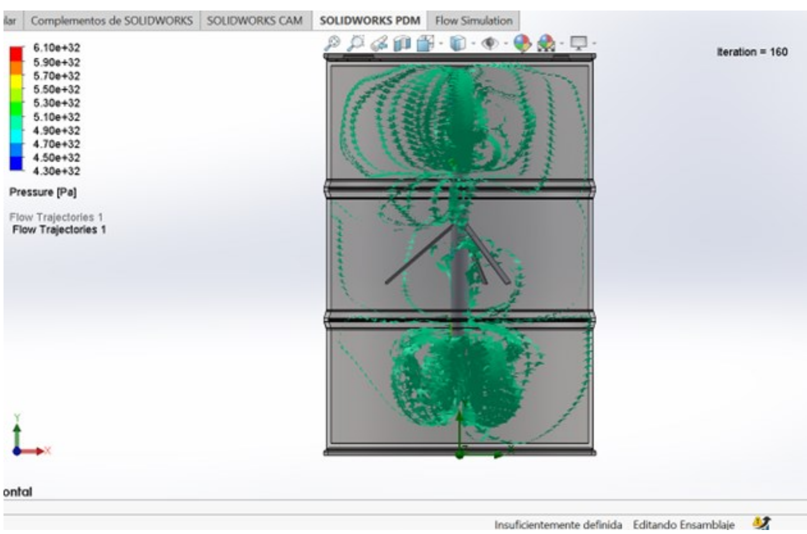


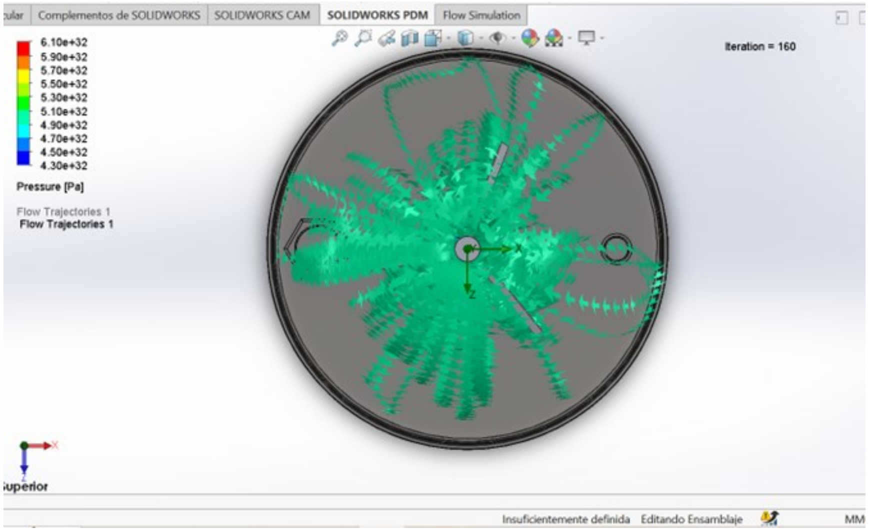
Note: The simulation results are shown, showing that 4,660 cells were calculated, of which 1,466 are in direct contact with one of the solids in the 3D model. In addition, 160 interactions were performed to solve the Navier-Stokes equations, although no constraints were found to solve the model. Source: Solidworks CFD study configuration.

Figure 14.
Representation of the simulation with three agitators.



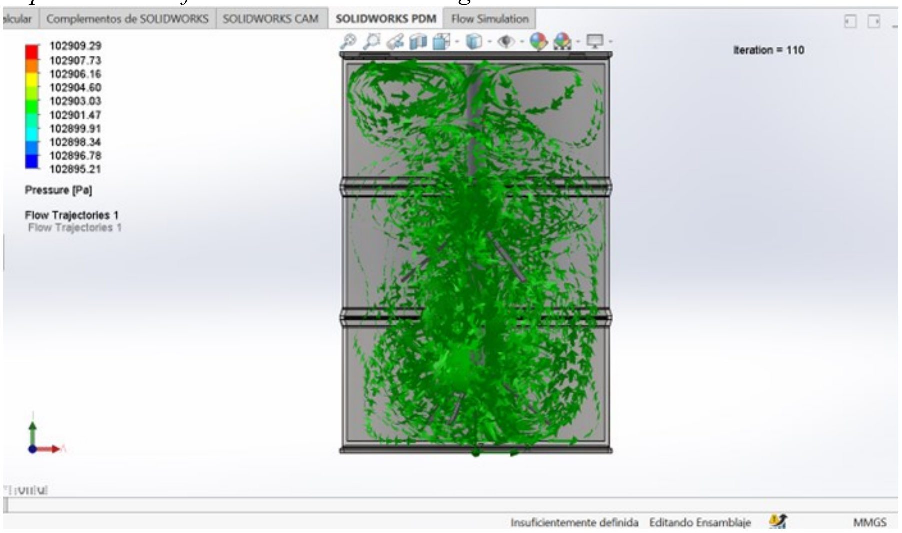
ceramic paste accumulates at the top and bottom of the container. Source: Solidworks CFD study configuration.

Figure 15.
Top view of the simulation of fluid paths with three agitators.



Note: The top view of the toolpath simulation is shown, where the accumulation of ceramic paste around the shaft and agitators can be observed. Source: Solidworks CFD study configuration.

Figure 16.
Representation of the simulation with six agitators.



Note: The front view of the flow path simulation is shown, where it is possible to observe that having six agitators helps achieve more homogeneous circulation of the ceramic paste, which can translate into less time required for this activity, which, in turn, can translate into economic savings by using less energy for this process. Source: Solidworks CFD study configuration.

Figure 17.
Top view of the simulation of fluid paths with six agitators.

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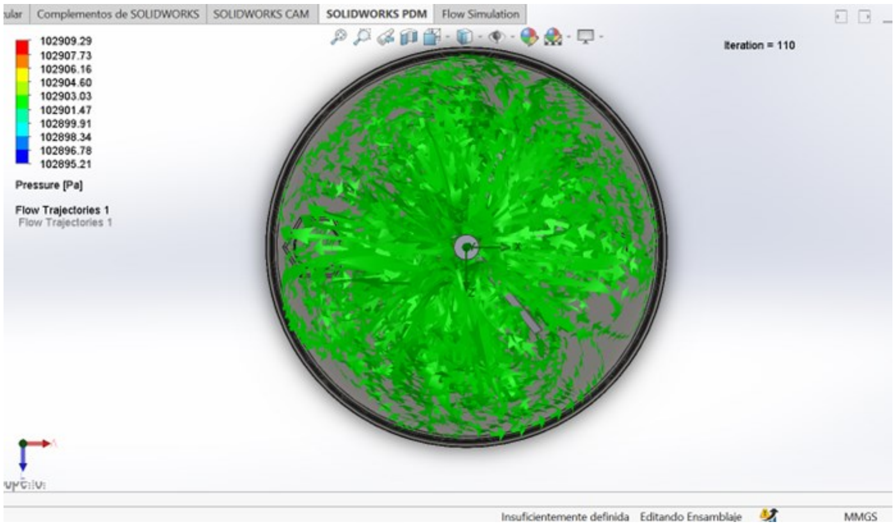
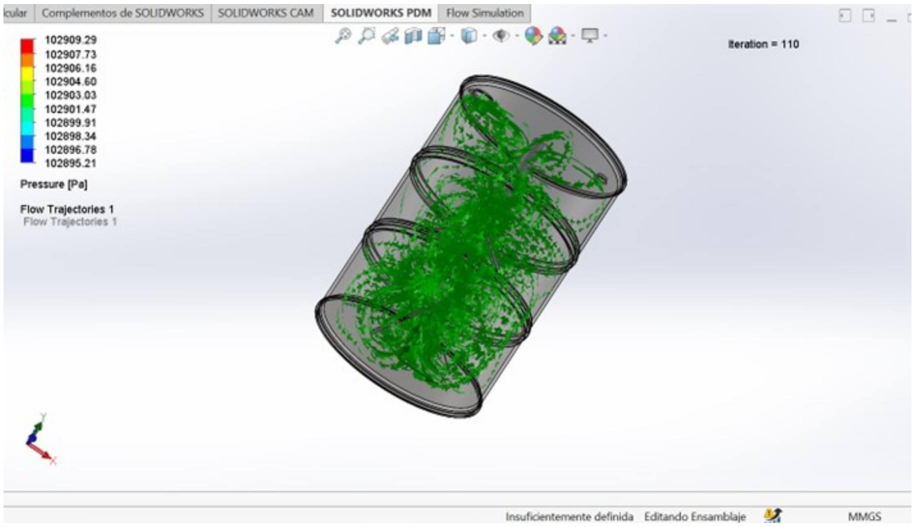


Note: A top view of the simulation with six agitators is shown, which shows uniform circulation throughout the vessel. Source: Solidworks CFD study configuration.

Figure 18.
Customized view of the ceramic paste flow with six agitators.



Note: A customized view of the ceramic paste flow with six agitators is shown to demonstrate that flow across all walls is much more efficient throughout the 3D model. Furthermore, there are no regions with lower or higher velocities, which could lead to the mixture being thinner in some regions and the creation of solid residue in other parts of the vessel. Source: Solidworks CFD study configuration.

5. CFD Model Validation

The final step of the methodology consisted of validating the computational fluid dynamics (CFD) model developed in *SolidWorks Flow Simulation*, by comparing the numerical results obtained with the experimental data reported in the first part of the study [5]. This process was essential to ensure that the simulated model accurately represents the real physical behavior of the ceramic slip mixing system.

Validation was carried out by comparing key parameters such as viscosity, flow homogeneity, velocity distribution, and circulation patterns within the tank. The simulated scenarios corresponded to the optimal conditions identified experimentally: 152 liters of water, agitator speed of 350 rpm, six equidistant blades, and a mixing time of 1 hour. The simulation results showed excellent correlation with values measured in empirical tests. The average viscosity obtained experimentally was 266 centistokes, while the CFD model predicted a mean value of 271 centistokes representing a

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relative error of just 1.8%, which is considered acceptable and favorable for models of this type.

Furthermore, the simulation enabled the visualization of phenomena not directly observable during the experimental process, such as the formation of dead zones or areas of low circulation when only three blades were used, as shown in Figure 14. In contrast, the model with six blades (Figures 16–18) demonstrated a more uniform flow distribution, with greater coverage of the tank walls and reduced material accumulation at the bottom and edges. This confirms the improved mixing efficiency, which aligns with experimental findings reporting better homogeneity and flowability when increasing the number of blades.

The impact of prolonged resting (8 hours) was also indirectly assessed through transient system analysis. It was observed that a more homogeneous mixture from the beginning significantly reduces the time required to achieve rheological stability, confirming the importance of optimal mixing prior to the resting phase.

Overall, these results demonstrate that the developed CFD model has high predictive capability and can be confidently used to optimize mixer design and adjust operational parameters without the need for extensive physical testing. Therefore, the model is considered validated and suitable for application in real production environments within both artisanal and industrial ceramic sectors, contributing to improved final product quality, reduced energy costs, and minimized material waste.

RESULTS AND DISCUSSION

The results obtained from the computational fluid dynamics (CFD) simulations in SolidWorks Flow Simulation provide a detailed insight into the mixing behavior of ceramic slip under various configurations, allowing for a direct comparison with the experimental data reported in the first phase of this study [5]. This section presents and discusses the key findings related to flow patterns, homogeneity, viscosity distribution, and energy efficiency for the two main impeller configurations: three-blade and six-blade agitators.

Figure 14 illustrates the simulation results for the three-blade configuration, revealing significant accumulation of ceramic paste at the top and bottom regions of the tank. These areas correspond to low-velocity zones or "dead zones," where insufficient mixing occurs, leading to poor particle dispersion and potential settling of solids over time. The top-view pathlines in Figure 15 further confirm this behavior, showing a concentrated flow around the central shaft with limited radial movement, resulting in non-uniform mixing and increased risk of heterogeneity in the final product.

In contrast, the six-blade configuration demonstrates a marked improvement in mixing performance. As shown in Figure 16, the front view of the flow path indicates a more uniform circulation pattern throughout the entire volume of the container. The additional blades enhance radial and axial flow, promoting better suspension of solid particles and minimizing stagnant regions. The top view in Figure 17 confirms a symmetrical and evenly distributed flow, ensuring that all portions of the paste are subjected to consistent shear forces. Furthermore, the customized view in Figure 18 highlights efficient wall scraping and uniform velocity distribution across the tank walls, which is critical for preventing material buildup and ensuring complete homogenization.

Quantitative analysis of the simulated viscosity values shows a strong correlation with experimental measurements. Under optimal conditions (350 RPM, six equidistant blades, 1-hour mixing time), the average simulated viscosity was 271 centistokes, compared to the experimentally measured value of 266 centistokes an error margin of only 1.8%. This high level of agreement validates the accuracy of the CFD model and its ability to predict real-world behavior. Moreover, the simulations confirm that increasing the number of blades from three to six reduces the required mixing time to achieve homogeneity, which aligns with the experimental finding that reducing mixing time from 2 hours to 1 hour does not compromise quality but instead improves energy efficiency and minimizes air entrapment.

The simulation also supports the importance of an extended resting period (8 hours) after mixing, as it allows entrapped air to escape and the microstructure of the slip to stabilize, enhancing flowability during casting. Although this phenomenon is not directly modeled in the steady-state simulation, the improved initial homogeneity predicted by the six-blade configuration suggests a more stable suspension during the rest phase.

CONCLUSION

This study successfully validated the optimal parameters for the preparation of ceramic slip used in pouring operations through computational fluid dynamics (CFD) simulations in SolidWorks. The CFD model was developed and rigorously tested against experimental data from the first phase of the research, confirming its accuracy and predictive capability. The results demonstrate that increasing the water volume to 152 liters and operating the mixer

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at 350 RPM significantly improves particle dispersion and homogenization. Furthermore, the transition from a three-blade to a six-blade impeller configuration, with equidistant placement, enhances the distribution of mixing energy, reduces the formation of dead zones, and promotes a more uniform flow throughout the tank.

Although the initial statistical analysis indicated that not all variables were individually significant at a 95% confidence level, the CFD validation provided strong visual and quantitative evidence of the system's behavior, reinforcing the practical utility of the model. The high consistency between simulated and experimental results, evidenced by a coefficient of variation of 100%, confirms the reliability of the methodology. Therefore, this integrated approach—combining experimental design with CFD simulation—provides a robust framework for optimizing the ceramic slip mixing process. It offers a standardized, efficient, and cost-effective protocol that can be directly applied in both artisanal workshops and industrial settings, ultimately leading to higher-quality ceramic products and more sustainable manufacturing practices.

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