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To obtain the master's degree

Option: Drilling

-Title-

**Eulerian Multiphase Numerical Simulation of a
Granular Flow**

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Abstract:

This study investigates the solid-liquid mixing dynamics within a mechanically stirred tank using numerical simulation. The analysis focuses on the behavior of a turbulent flow generated by impellers, combining both axial and axial-radial flow patterns to interact with the fluid. By tracking particle movement from an initial state of gravitational sedimentation to a fully developed suspension, the results demonstrate how the mechanical energy induced by the rotating blades effectively overcomes gravity. This generalized approach evaluates mixing efficiency and ensures continuous phase homogeneity in industrial applications

Keywords: Simulation, Multiphase Flow, Drilling Fluid, Turbulent flow, Phase homogeneity.

الملخص :

تتناول هذه الدراسة ديناميكية المزج بين الصلب والسائل داخل خزان مزود بخلاط ميكانيكي باستخدام المحاكاة العددية. يركز هذا البحث بشكل عام على سلوك الجريان الاضطرابي الناتج عن حركات المحرض، والذي يجمع بين التدفق المحوري والتدفق الشعاعي للتفاعل مع المائع. ومن خلال تتبع حركة الجسيمات من حالة الترسيب الأولي بفعل الجاذبية إلى التعليق الكامل، تُظهر النتائج كيف تتغلب الطاقة الميكانيكية الناتجة عن دوران الشفرات على تأثير الجاذبية. وتسمح هذه الدراسة الشاملة بتقييم كفاءة الخلط وضمان استمرارية تجانس الأطوار في التطبيقات الصناعية.

الكلمات المفتاحية:

محاكاة، الجريان متعدد الأطوار، سائل الحفر جريان اضطرابي، تجانس الأطوار

Résumé:

Cette étude examine la dynamique de mélange solide-liquide au sein d'une cuve agitée mécaniquement par le biais de la simulation numérique. L'analyse se concentre sur le comportement d'un écoulement turbulent généré par des agitateurs, combinant un écoulement axial et radial pour interagir avec le fluide. En suivant le mouvement des particules depuis leur état initial de sédimentation jusqu'à leur suspension complète, les résultats démontrent comment l'énergie mécanique induite par la rotation des pales permet de surmonter les effets de la gravité. Cette approche globale permet d'évaluer l'efficacité du brassage et de garantir le maintien d'une homogénéité continue des phases en milieu industriel.

Mots-clés: Simulation, Écoulement Multiphasique, Fluide de Forage, Écoulement turbulent, Homogénéité des phases.

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Dedication

To ALLAH, the Almighty, who has granted us the strength to pursue our dreams and surrounded us with wonderful people who helped us achieve our goals. We dedicate this project to You with the utmost humility and gratitude—**ALHAMDULILLAH**.

We dedicate this work to our beloved Parents, for the endless sacrifices, love, and encouragement you have provided us throughout our academic lives. This accomplishment are the fruit of your prayers and the efforts you have made to pave the way for our success. To our beloved siblings, for the profound love, continuous support, and motivation you have brought into our lives.

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Summary

Acknowledgement	III
Dedication	IV
List of figures and tables	IX
Nomenclature	XI
GENERAL INTRODUCTION	XIII
Chapter1: Generalities of Drilling and Equipment	XV
1.1 Introduction:	2
1.2 Definition of Drilling:	2
1.2.1 Definition of Drilling Rig:	3
1.2.1.1 Classification of the Drilling Rig:	4
1.3 Rotary Drilling Principle:	4
1.3.1.1 Rig Systems:	5
1.3.1.2 Hoisting system:	5
1.3.2 Rotary system:	6
1.3.3 Power system:	7
1.3.4 Well control Safety system:	8
1.3.5 Circulation system:	8
1.3.6 Drilling fluid circuit:	8
1.3.7 Pumping System: (MUD PUMPS)	10
1.3.7.1 Surface Cleaning system:	10
1.3.7.2 Intermediate Separation: Hydro cyclones (Desander & Desalter)	12
Hydro cyclones	12
Desalter:	12
1.3.7.3 The surface storage system:	13
1.4 Conclusion:	14
Chapter2: Drilling Fluid Systems and Surface Preparation	2
2.1 Introduction:	18
2.1.1 Definition of Drilling fluid:	18
2.1.2 Functions of Drilling Fluids:	18

Summary

2.2	Types of Drilling Fluids:	19
2.2.1	Dispersed (classic) drilling fluids:	19
2.2.2	Inhibitive drilling fluids:.....	19
2.2.3	Salt-based fluids:	20
2.2.4	Polymer-based fluids:.....	21
2.2.5	Fluids based on petroleum products:	21
2.2.6	Clear fluids:	23
2.3	The rheological properties of drilling fluids:	23
2.3.1	Thixotropic properties of drilling fluids:.....	26
2.3.1.1	Drilling Fluid Suspension and Mixing Dynamics:	27
2.3.2	The Mechanical agitators:	27
2.3.2.1	The Agitators Impellers:	28
2.3.2.2	Radial Flow Impellers:	29
2.3.2.3	Axial Flow Impellers:	29
2.4	Conclusion:.....	30
Chapter3:	NUMERICAL MODELING AND SIMULATION SETUP	17
3.1	Introduction	33
3.2	Physical and geometrical description	33
3.2.1	Initial Geometrical Representation	33
3.2.2	Geometrical modeling and meshing.....	34
3.2.2.1	Boundary:.....	35
3.2.2.2	Meshing.....	36
3.3	Physical Models.....	38
3.3.1	Gravity Effect:	38
3.3.2	Multi-phase Model:	39
3.3.3	Turbulence Modeling	39
3.4	Material Properties	39
3.4.1	Water (Primary Phase):	39
3.4.2	Sand (Secondary Phase).....	39

Summary

3.5	Cell Zone Conditions and Rotational Modeling	40
3.6	Initialization and Phase Distribution	40
3.6.1	Initialization Strategy	40
3.6.2	Sand Injection Using Patch.....	41
3.7	Boundary conditions	41
3.8	User-Defined Function (UDF) Implementation	41
3.8.1	Mathematical Formulation	41
3.8.2	Role of the UDF in the Simulation.....	45
3.9	The calculation parameters.....	45
3.9.1	Relaxation Factors	45
3.9.2	Numerical Parameters	45
Chapter4:	Results And Discussion.....	41
4.1	Introduction	46
4.2	Residual Analysis and Numerical Behavior	46
4.3	Evolution of the Mixing Process.....	47
4.3.1	Initial State (Step 0 – Step 10).....	47
4.3.2	Early Stage (Step 10 – Step 40)	48
4.3.3	Intermediate Stage (Step 40 – Step 100)	51
4.3.4	evolution of scaled residuals showing convergence behavior in multiphase mixing: 54	
4.3.5	Velocity Interpretation	56
4.3.6	Fully Developed Regime (Step 200 and beyond)	57
4.4	Flow Structure and Hydrodynamic Behavior	61
4.5	Evolution of Sand Distribution (Quantified Interpretation)	62
	The Pressure:.....	63
4.6	Interaction Between Gravity and Turbulence	63
4.6.1	Turbulent Kinetic Energy Distribution	63
4.6.2	Interaction Between Gravity and Turbulence	64
4.7	Relation Between Residuals and Mixing	65
4.8	General Discussion	66

Summary

4.9	Conclusion.....	67
	Conclusion	68
	References	71

List of figures and tables

Figure 1-1 : oil wellbore encased in steel and cement.....	3
Figure 1-2: onshore rig - ENAFOR 37 / Deepwater rig	3
Figure 1-3 : Rotary Drilling rig.....	5
Figure 1-4 the hoisting system of rig (1)	6
Figure 1-5: the rotary system of a rig (2).....	7
Figure 1-6: The power system of a rig.....	7
Figure 1-7: BOP stack (6)	8
Figure 1-8: Drilling fluid circuit (7).....	9
Figure 1-9 : CAMEROON drilling pump.....	10
Figure 1-10: Shale shaker	11
Figure 1-11: poor boy and vacuum degasser	11
Figure 1-12: Hydroceles	12
Figure 1-13 : Decanting centrifuge	13
Figure 1-14: Drilling mud agitator.....	14
Figure 2-1: the rheograms of Newtonian fluids.....	24
Figure 2-2 : The rheograms of Bingham fluids.....	25
Figure 2-3: Characteristic curves of gelation of drilling fluids.....	26
Figure 2-4: horizontally / vertically mounted unit.....	28
Figure 2-5: Radial Flow Impellers [12].	29
Figure 2-6: Axial Flow Impellers [12].	30
Figure 3-1: equipment sketch.....	34
Figure 3-2: tank body with internal equipment.....	35
Figure 3-3: rotating blades and runny int.....	35
Figure 3-4: fluid_mrf_1-1 and fluid_mrf_2-0.....	36
Figure 3-5 full tank and impellers mesh	37
Figure 3-6 : upper impeller mesh.....	37
Figure 3-7: lower impeller mesh.....	38
Figure 4-1 sand distribution in bottom of tank	47
Figure 4-2: sand water distribution in tank	47
Figure 4-3: Graph of variables at the first iterations.....	48
Figure 4-5 volume fraction of sand on the lower blade	49
Figure 4-4 volume fraction of sand on YZ view.....	49
Figure 4-6: Evolution of scaled residuals transient simulation showing periodic convergence behavior associated with time stepping (from 0 to 300 iterations).....	49
Figure 4-7 Evolution of scaled residuals during transient simulation showing periodic convergence behavior associated with time stepping (from 525 to 650).....	50

List of figures and tables

Figure 4-8 volume fraction on lower blade.....	52
Figure 4-9 volume fraction on YZ view	52
Figure 4-10: sand velocity on lower blade.....	52
Figure 4-11: evolution of scaled residuals showing convergence behavior in multiphase mixing	54
Figure 4-12 evolution of sand volume fraction on YZ view.....	55
Figure 4-13: evolution of sand volume fraction on the lower blade.....	55
Figure 4-14: velocity evaluation	57
Figure 4-15 sand volume fraction on YZ view	58
Figure 4-16: Sand Velocity	58
Figure 4-17: sand volume fraction on lower blade at 200 steps	59
Figure 4-18: Global evolution of scaled residuals over 200-time steps showing transient convergence behavior in a multiphase mixing simulation.....	59
Figure 4-19: static pressure contours showing pressure gradients generated by impeller rotation during the mixing process	63

Nomenclature

Symbol	Description	Unit
API	American Petroleum Institute	—
BHA	Bottom Hole Assembly	—
BOP	Blowout Preventer	—
CFD	Computational Fluid Dynamics	—
$\vec{v}$	Velocity vector	m/s
$\vec{v}_q$	Velocity vector of phase q	m/s
U	Characteristic velocity	m/s
U_θ	Tangential velocity	m/s
u'	Turbulent velocity fluctuation	m/s
V_s	Settling velocity	m/s
p	Pressure	Pa
∇p	Pressure gradient	Pa/m
g	Gravitational acceleration	m/s^2
k	Turbulent kinetic energy	m^2/s^2
C_μ	Empirical turbulence constant	—
Re	Reynolds number	—
R	Residual value	—
r	Radial distance from shaft	m
d	Particle diameter	m
D	Characteristic diameter	m
t	Time	s
M_{pq}	Interphase momentum exchange	N/m^3
n	Number of phases	—
q	Phase index	—
α	Phase volume fraction	—
α_l	Liquid volume fraction	—
α_s	Solid volume fraction	—
ρ	Density	kg/m^3
ρ_q	Density of phase q	kg/m^3
ρ_s	Sand density	kg/m^3
ρ_f	Fluid density	kg/m^3
ε	Turbulence dissipation rate	m^2/s^3

Nomenclature

μ	Dynamic viscosity	$Pa.s$
μ_t	Turbulent viscosity	$Pa.s$
ω	Angular velocity	rad/s
τ_q	Stress tensor of phase q	Pa

GENERAL INTRODUCTION

General Introduction

The exploitation of hydrocarbon resources relies on efficient and safe drilling operations. Among the various systems involved in the drilling process, the drilling fluid circulation system plays a fundamental role. Drilling fluids are used to transport drilled cuttings to the surface, cool and lubricate the drill bit, maintain wellbore stability, and control formation pressures.

One of the main challenges encountered during drilling fluid preparation and storage is the sedimentation of solid particles. Due to the difference in density between the solid and liquid phases, particles tend to settle under the effect of gravity, which can affect the homogeneity and performance of the drilling fluid. To overcome this issue, mechanical agitators are commonly used to maintain the particles in suspension and ensure proper mixing.

Understanding the behavior of solid–liquid mixtures inside stirred tanks is therefore essential for improving mixing efficiency and reducing sedimentation. Experimental investigations, however, can be costly and time-consuming. Numerical simulation offers an effective alternative for studying the hydrodynamic behavior of such systems.

The objective of this work is to investigate the mixing process of a solid–liquid system inside a mechanically stirred tank and to evaluate the effectiveness of agitation in promoting particle suspension and distribution. The study aims to understand the mechanisms governing solid–liquid mixing and their impact on process performance to achieve the objectives of this study, the dissertation is organized into four chapters. The first chapter presents general information about drilling operations and the main equipment involved in the drilling process. The second chapter focuses on drilling fluid systems, their properties, functions, and surface preparation methods. The third chapter describes the numerical methodology adopted in this work, including the geometry, mesh generation, physical models, boundary conditions, and simulation setup. Finally, the fourth chapter presents and discusses the obtained results, with particular emphasis on the analysis of flow behavior, particle suspension, and mixing performance within the stirred tank

Chapter1: Generalities of Drilling and Equipment

Chapter 1: Generalities of Drilling and Equipment

1.1 Introduction:

Drilling is the process of creating a hole in a solid material such as metal, wood, rock, or soil, using a drill bit that rotates and applies force to the material. The purpose of drilling can vary, ranging from creating holes to fix screws or bolts, extracting natural resources like oil or gas, or collecting core samples for geological analysis.

Drilling can be done manually using portable tools or with machine tools. The drilling process can be complex and requires knowledge of the material being drilled, the type of bit used, the drilling speed and feed rate, as well as the necessary lubrication or cooling methods to prevent damage to the bit or the material.

As a drilling engineer, the objectives of petroleum drilling operations can be summarized as follows:

- **Safety:** Ensuring the safety of personnel, equipment, and the environment is the top priority. This involves implementing and strictly adhering to safety protocols, such as using personal protective equipment (PPE) and maintaining safety systems.
- **Efficiency:** Maximizing operational efficiency is crucial to reducing costs and minimizing downtime. This includes optimizing drilling parameters like rate of penetration (ROP), bit selection, and mud properties.
- **Precision:** Reaching the targeted well depth and location is crucial. This requires precise placement using advanced technologies, such as directional drilling and wellbore imaging tools.
- **Reservoir Evaluation:** Evaluating the reservoir to determine its characteristics (size, composition, producibility) is essential for maximization.

1.2 Definition of Drilling:

Drilling is the process of creating a wellbore, narrow, deep hole drilled into the earth's surface to access subsurface formations for the purpose of exploring, evaluating, and producing oil and natural gas. It involves the use of a drill bit attached to a drill string, which rotates and applies downward force to penetrate various geological layers. Then, casing is installed to isolate the production zones, ensuring well integrity, and facilitating safe and efficient extraction of hydrocarbons. [1]. (Figure 1.1)

Chapter 1: Generalities of Drilling and Equipment

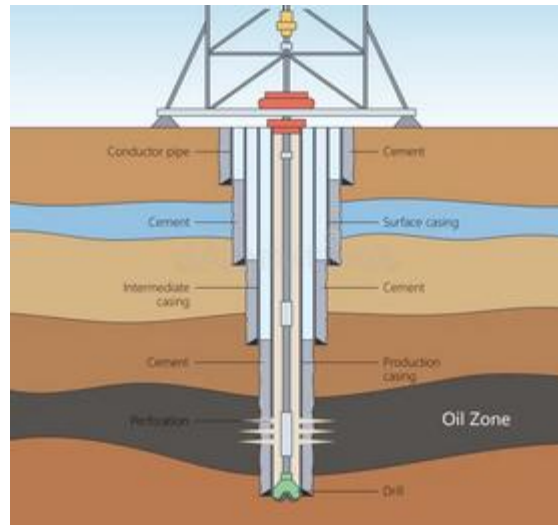


Figure 1-1 : oil wellbore encased in steel and cement

1.2.1 Definition of Drilling Rig:

The drilling rig is a complex assembly of equipment and machinery used to drill wells into the Earth's subsurface for the purpose of exploring and producing oil and gas. It serves as the operational base for all drilling activities, whether on land (onshore) or at sea (offshore). Drilling rigs vary in size and configuration depending on the depth, location, and objectives of the well, but all are designed to safely and efficiently penetrate geological formations. [1]. (Figure 1.2)



Figure 1-2: onshore rig - ENAFOR 37 / Deepwater rig

1.2.1.1 Classification of the Drilling Rig:

The drilling rig consists of a set of equipment, operational techniques, and highly qualified personnel. Rotary drilling rigs are generally classified into four categories based on the depth limits they can reach with 4 1/2" drill pipes and geological conditions:

- **Light rigs:** For depths less than 1200 m. Often portable or semi-portable.
- **Medium rigs:** For depths between 1200 and 2500 m.
- **Heavy rigs:** For depths between 2500 and 4000 m.
- **Ultra-heavy rigs:** For depths exceeding 4000 m. [2].

1.3 Rotary Drilling Principle:

Rotary drilling based on rotating a drill bit under applied weight to bore into the earth. A drill string, composed of drill pipes, transmits rotational power from the surface to the bit.

Drilling fluid, typically mud, is pumped down the drill string, exits through nozzles in the bit to cool and lubricate it, and carries the generated cuttings up the annulus (space between the drill string and the borehole) to the surface. This continuous circulation of drilling fluid is crucial for efficient drilling and maintaining borehole stability. (Figure 1.3)

For that the rotary drilling operation requires the execution of three main functions:

- Weight on bit (WOB)
- Rotation of the bit
- Mud injection (circulation under pressure)

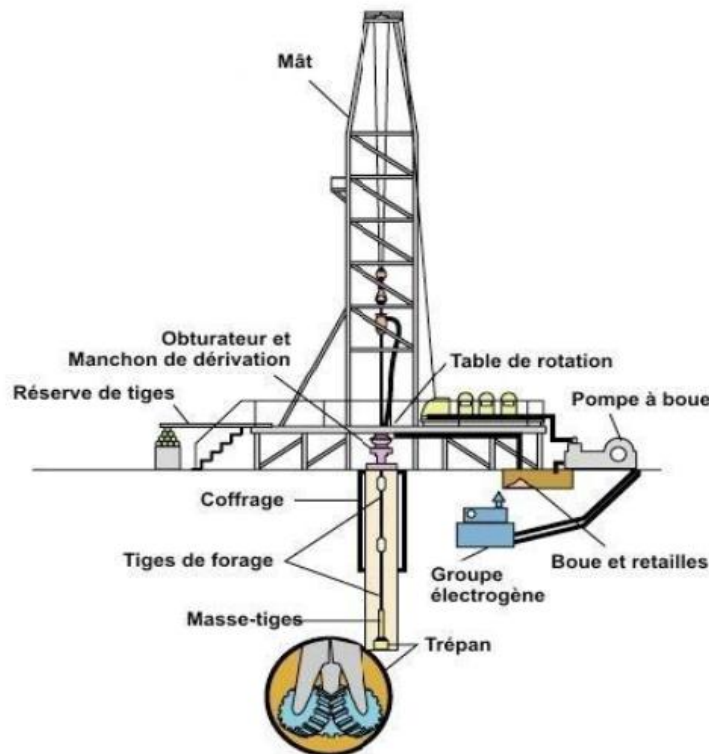


Figure 1-3 : Rotary Drilling rig

1.3.1.1 Rig Systems:

A drilling rig is a complex assembly of machinery used to bore holes into the Earth's surface for extracting oil, natural gas, water, or exploring mineral deposits. Its primary functions include rotating the drill bit, circulating drilling fluid, hoisting heavy tools, with power system and managing wellbore pressure to ensure safe and efficient extraction.

1.3.1.2 Hoisting system:

The Hoisting system is essential for lifting drill pipes, and casing in and out of the well. This system typically consists of the draw works (a large winch), the drilling line (a steel wire rope), the crown block (located at the top of the mast), and the traveling block (which moves vertically). (Figure 1.4) [3].

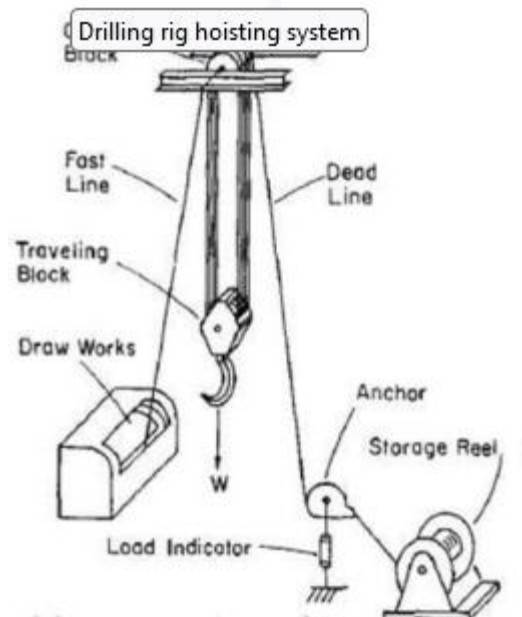


Figure 1-4 the hoisting system of rig (1)

1.3.2 Rotary system:

The rotary system in a drilling rig is responsible for rotating the drill string and the drill bit at the bottom of the wellbore, allowing the bit to cut through subsurface rock formations. It provides the mechanical motion necessary to advance the borehole during drilling operations. It includes the rotary table (or top drive-in modern rigs),

Kelly (in traditional setups), swivel, and drill string. The rotation is transmitted from the rig's power source through these components down to the drill bit. (Figure 1.5)

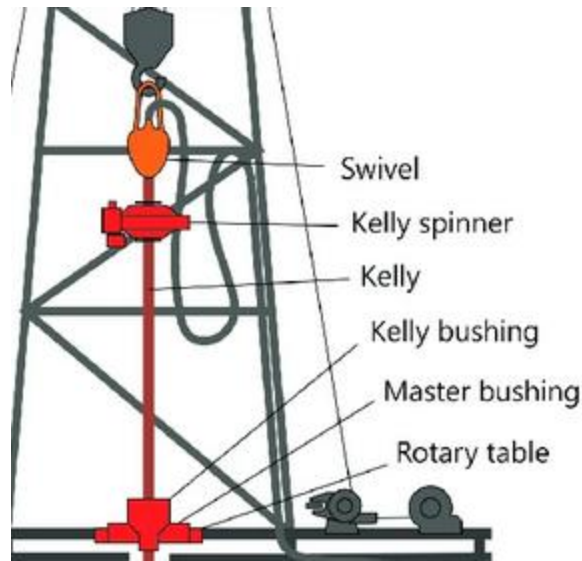


Figure 1-5: the rotary system of a rig (2)

1.3.3 Power system:

The power system in a drilling rig supplies the energy required to operate all major rig components and systems, including the hoisting, rotary, circulating, and well control systems. It is the backbone of the rig's functionality, ensuring that mechanical, hydraulic, and electrical equipment can perform efficiently and reliably during drilling operations. This system typically consists of prime movers (such as diesel engines or gas turbines), generators, electric motors, and power distribution panels. In modern rigs, power systems are often centralized and automated to optimize energy use and reduce emissions. The transmission of the power can be either in direct current (DC) or alternating current (AC). [4]. (Figure 1.6)

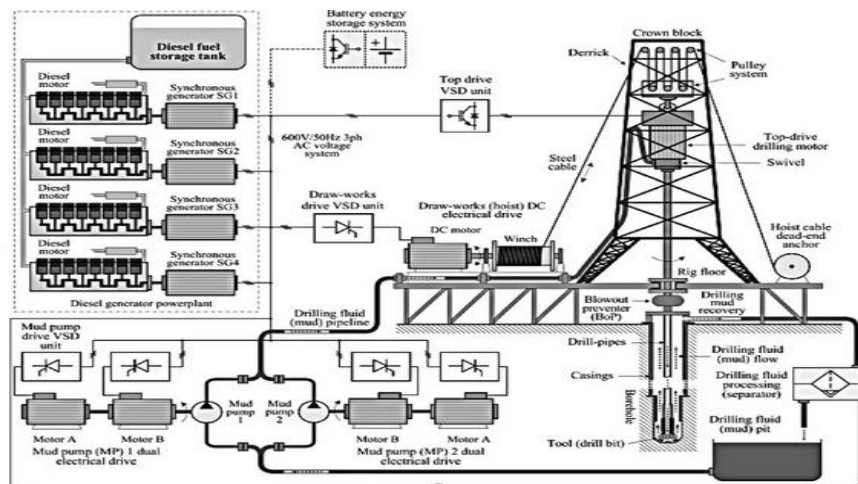


Figure 1-6: The power system of a rig

1.3.4 Well control Safety system:

When drilling wells in formations suspected of having high pressure, to prevent a gas or oil blowout, the wellhead is equipped with safety sealing devices called Blowout Preventers (BOP). The BOP is an essential safety equipment composed of hydraulic and mechanical valves (annular, blind rams, shear rams, pipe rams) that can quickly seal the well in an emergency to prevent uncontrolled eruptions. (Figure 1.7)



Figure 1-7: BOP stack (6)

1.3.5 Circulation system:

The circulating system of a drilling rig, often described as the "heart" of the operation. It is a continuous system of pumps, distribution lines, storage tanks, storage pits, and cleansing units that allows the drilling fluid to fulfill its primary objectives.

1.3.6 Drilling fluid circuit:

In oil and gas extraction, the design of drilling fluid circuits involves the specification of circulation rate, pressure, temperature, and other parameters. This design must be based on a range of general principles that govern the performance capabilities and operational characteristics of drilling-fluid circuits. Each of these principles is defined by specific tasks that the component must achieve, how the configuration of that component affects the performance of the overall circuit, and the implications of current circuit performance on the design of other components. Analysis of these principles yields insight into the design considerations for drilling-fluid circuits in variable formations, enabling the selection of parameters that best satisfy the principles to achieve optimal performance objectives. (Figure 1.8)

Chapter 1: Generalities of Drilling and Equipment

In conventional drilling, the drilling fluid circuit is:

- **Surface System:** Mud is drawn from the mud pits/tanks by high-pressure mud pumps.
- **Down hole Passage:** The fluid flows through the standpipe, high-pressure rotary hose, swivel, and into the drill string.
- **Bit Outlet:** The fluid travels down the inside of the drill pipe and drill collars, exiting through the drill bit nozzles, where its hydraulic energy helps break the rock.
- **Return Path (Annulus):** The fluid, now carrying rock cuttings, flows upward through the annulus (the space between the outside of the drill pipe and the wellbore wall) back to the surface.
- **Surface Cleaning:** The returning mud passes through solids control equipment, primarily shale shakers, which remove cuttings, before the clean fluid returns to the mud pits [7].

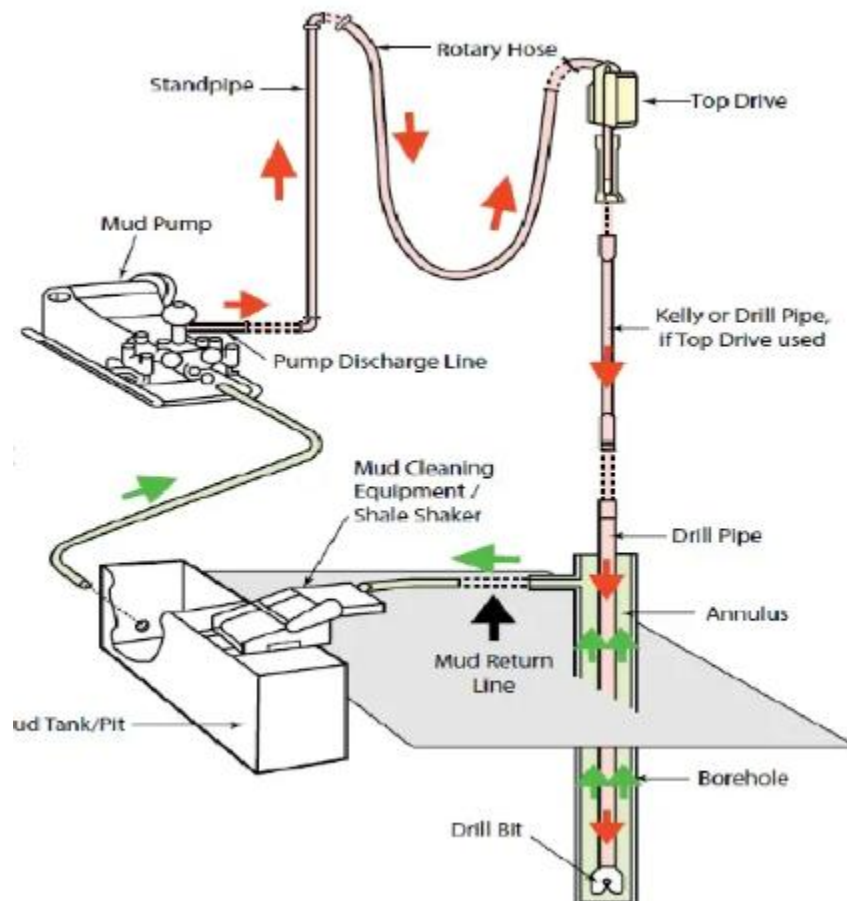


Figure 1-8: Drilling fluid circuit (7)

1.3.7 Pumping System: (MUD PUMPS)

Mud pumps are essential for injecting mud into the wellbore and circulating it throughout the system. They can be driven by electric motors, diesel engines, or gas turbines. The pump capacity must be sufficient to supply the required volume and maintain necessary pressure.

- **Types of Pumps:**

Centrifugal Pumps: Commonly used for mixing, transferring, and supercharging at surface level. They provide high volume at low pressure.

Piston Pumps (Reciprocating): More complex and expensive but provide the high pressure required for deep drilling. They use cylinders and pistons to pump fluid. [7]. (Figure 1.9)



Figure 1-9 : CAMEROON drilling pump

1.3.7.1 Surface Cleaning system:

The surface cleaning system for drilling mud, universally known as the Solids Control System (SCS), is the critical infrastructure on a rig designed to maintain the rheological properties of the drilling fluid, protect downhole tools, and prevent excessive wear on surface pumps.

Here we see the technical breakdown of the standard surface cleaning sequence:

- **Primary Separation: Shale Shakers**

The flow line directs the mud returning from the annulus directly over the shale shakers. This is the first and most critical line of treatment.

Mechanism of SHALE SHAKER: Vibrating screens apply high G-forces to separate larger drill cuttings from the liquid phase.

Typically removes particles from 74 microns up to several millimeters, depending on the API screen mesh size used. [7]. (Figure 1.10)



Figure 1-10: Shale shaker

- **Gas Removal: Degassers**

Before the mud is processed by centrifugal pumps for finer separation, entrained gas must be removed to prevent pump cavitation and maintain accurate mud density.

In this operation we have:

Mud/Gas Separator (Poor Boy Degasser): Used for large volumes of free gas (kick situations).

Vacuum Degasser: Used continuously to extract micro-bubbles of entrained gas by spreading the mud into thin layers over baffles under a vacuum. (Figure 1.11)

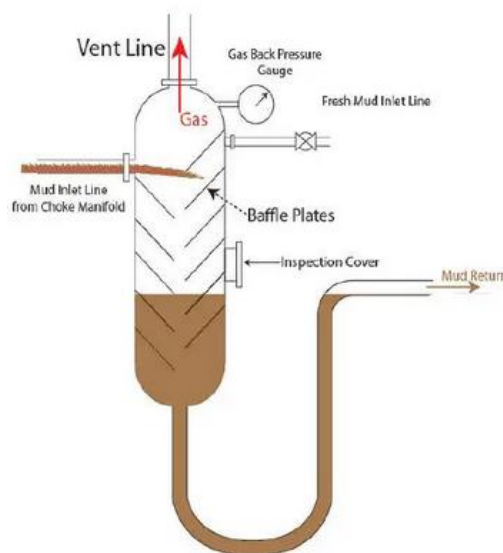


Figure 1-11: poor boy and vacuum degasser

Chapter 1: Generalities of Drilling and Equipment

1.3.7.2 Intermediate Separation: Hydro cyclones (Desander & Desalter)

Hydro cyclones use centrifugal force rather than physical screens to separate finer low-gravity solids (LGS) from the fluid.

Desander:

Features larger cones (10 to 12 inches). It removes particles in the 40 to 74-micron range.

Desalter: Features smaller cones (4 inches) operating at higher pressure drops. It handles the 15 to 40-micron range.

Mud Cleaner: Often, hydro cyclones are mounted directly above a high-mesh vibrating screen. The hydro cyclone underflow drops onto the screen to recover the liquid phase and barite while discarding the drilled solids. (Figure 1.12)



Figure 1-12: Hydrocycles

- **Fine Solids Recovery: Decanting Centrifuge**

For ultra-fine particulate and managing weighted mud systems, the decanting centrifuge is deployed.

Mechanism: A high-speed rotating bowl and a scroll conveyor physically push the heavier, finer solids to the discharge port. Can remove particles down to 2 to 10 microns. (Figure 1.13)



Figure 1-13 : Decanting centrifuge

1.3.7.3 The surface storage system:

The surface storage system is divided into functional zones to ensure continuous operations and maintain well integrity.

- **The Active System:**

This is the heart of the circulating system, containing the mud that is actively being pumped down the drill string and returning up the annulus.

The Suction Pit (or Tank): This is the final tank in the active sequence. Mud here has passed through the entire solids control system (shakers, degassers, hydro cyclones, centrifuges) and is clean and properly weighted. The main rig pumps draw fluid directly from this pit to pump down hole.

The Mixing Pit: Positioned upstream of the suction pit. This tank is tied into the mud mixing hoppers. It is where raw materials (barite, bentonite, polymers, and chemical additives) are sheared into the system to adjust density, viscosity, and fluid loss properties before the mud reaches the suction pit.

Intermediate/Return Pits: These tanks hold the fluid as it transitions from the solids control equipment toward the mixing and suction pits, allowing for additional settling time for ultra-fine drilled solids that escaped mechanical separation. [7].

- **Fluid Suspension and Agitation:**

Chapter 1: Generalities of Drilling and Equipment

Because drilling muds are thixotropic and often heavily weighted with barite, the mud must be kept in constant motion while stored to prevent the weighting agents and suspended solids from settling to the bottom and "sanding up" the tanks.

Mechanical Agitators: Large, motor-driven impellers installed in almost every active and reserve tank to provide continuous bulk shearing and blending of the fluid. (Figure 1.14)

Mud Guns: High-pressure nozzles submerged in the tanks, powered by centrifugal pumps. They utilize the fluid's own velocity to sweep the corners and "dead zones" of square tanks where mechanical agitators cannot reach.

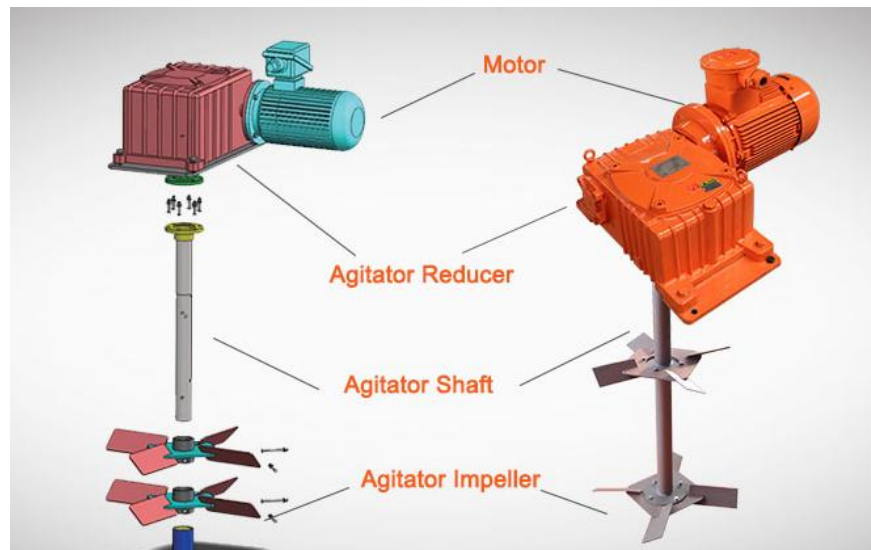


Figure 1-14: Drilling mud agitator

1.4 Conclusion:

In this Chapter we see that the rotary drilling process relies on the seamless integration of massive and complex mechanical systems power, hoisting, rotary, and well control to safely construct a wellbore and reach target reservoirs.

However, as highlighted throughout this chapter, none of these mechanical systems can function effectively without the continuous support of the circulating system. It acts as the true lifeblood of the rig, responsible for carrying away the cuttings, stabilizing the wellbore, and cooling the drill bit.

The efficiency of this circulating system is heavily dependent on the surface equipment's ability to properly store, treat, and continuously condition the drilling mud before it is pumped back down

Chapter 1: Generalities of Drilling and Equipment

hole. While the rig's structural components provide the necessary physical force, their success is ultimately dictated by the quality and consistency of the fluid being circulated.

Consequently, to fully understand the mechanics of surface mixing and the vital role of specific equipment like mud agitators, it is important to first understand the physical nature of the fluid they are processing.

This necessity leads directly into the following chapter, which will explore the composition, rheological properties, and surface preparation dynamics of drilling fluid systems.

Chapter2: Drilling Fluid Systems and Surface Preparation

2.1 Introduction:

As established in the previous chapter, the mechanical prowess of a drilling rig relies entirely on the circulating system to function safely and efficiently. The core of this system and the most critical component of the entire well-construction process is the drilling fluid, commonly referred to as drilling mud. This fluid is not merely a simple transport medium; it is a highly engineered, complex mixture designed to perform multiple critical functions simultaneously, from maintaining hydrostatic wellbore pressure to cooling the bit and suspending excavated solids.

2.1.1 Definition of Drilling fluid:

Drilling fluid or drilling mud is a specialized, viscous mixture circulated through the wellbore during drilling to lubricate the bit, remove rock cuttings, and control subsurface pressures. It is critical for stability, as its density prevents formation fluids from entering the well and stops the borehole from collapsing. [8].

2.1.2 Functions of Drilling Fluids:

A drilling fluid, or mud, is any fluid that is used in a drilling operation in which that fluid is circulated or pumped from the surface, down the drill string, through the bit, and back to the surface via the annulus. [8].

Drilling fluids satisfy many needs in their capacity to do the following:

- Suspend cuttings (drilled solids), remove them from the bottom of the hole and the well bore, and release them at the surface
- Control formation pressure and maintain well-bore stability
- Seal permeable formations
- Cool, lubricate, and support the drilling assembly
- Transmit hydraulic energy to tools and bit
- Minimize reservoir damage
- Permit adequate formation evaluation
- Control corrosion
- Facilitate cementing and completion
- Minimize impact on the environment

- Inhibit gas hydrate formation

The most critical function that a drilling fluid performs is to minimize the concentration of cuttings around the drill bit and throughout the well bore. In so doing, the fluid itself assumes this cuttings burden, and if the cuttings are not removed from the fluid, it very quickly loses its ability to clean the hole and creates thick filter cakes. To enable on-site recycling and reuse of the drilling fluid, cuttings must be continually and efficiently removed. [8].

2.2 Types of Drilling Fluids:

Drilling fluids are classified according to the type of base fluid and other primary ingredients:

2.2.1 Dispersed (classic) drilling fluids:

These fluids are based on the water-clay system (diluted solution with bentonite in water with a density of 1400-1600kg/m³) and therefore meet the stability, clogging and gelling requirements necessary for drilling.

Prepared on the surface from bentonite clays with good colloidal and dispersive properties, these fluids are used for drilling surface intervals or areas with loss of circulation where, as a rule, mud with high viscosity and gelation, without other special properties, is required.

In case of crossing clayey rocks that disperse or swell, productive strata or when the preparation clay does not provide the desired structural properties, these muds are treated with reduced amounts of fluidizers, filter reducers, stabilizers of the properties at high temperatures or at the action contaminated, lubricants, antifoams, becoming treated mud.

During the contact with the aqueous phase of the fluid, the clayey walls of the borehole lose stability or the mud becomes heavily contaminated, which can lead to frequent, expensive and beyond certain ineffective treatments, which is why their field of applicability is often reduced to simple geological conditions.

The clogging cake deposited by such a drilling fluid is chemically insoluble (in acid solutions), and the non-inhibitory filtrate can lead to the dispersion of clay minerals contained in the reservoir rock matrix. [9-10].

2.2.2 Inhibitive drilling fluids:

The fluids in this category are based on the whole water-clay system, but having a main role in ensuring the stability of the system and imprinting a strong inhibitory character on the aqueous

Chapter 2: Drilling Fluid Systems and Surface Preparation

environment, it is fulfilled by the addition of electrolytes, protective polymers, surfactants, certain fluidizers, etc.

Inhibitive drilling fluids prevent or delay the hydration, swelling and dispersion of clay rocks and at the same time show high inertia to classic contaminants such as clays, electrolytes and high temperatures.

They are used when traversing thick intervals of marls and clays sensitive to water, to reduce drilling difficulties generated by rock-fluid contact, when opening productive layers with clay intercalations (dirt).

In general, the main disadvantage of inhibitory drilling fluids is, moreover, as with dispersed drilling fluids, the failure to meet the criterion of chemical solubility of the system additives.

The clogging cake deposited by such a drilling fluid is chemically insoluble (in acid or oxidant solutions).

2.2.3 Salt-based fluids:

Fluids with sodium chloride have inhibition capacity, through their flocculant and aggregation effect. Salty fluids are those that have more than 1g NaCl/100cm³ filtered and they can be born by contaminating the fresh muds with dissolved salt from the traversed rocks or with the water penetrated from the layers in the well, by using sea water in their preparation or by the intentional addition of salt.

The inhibitory capacity of salt-based fluids depends on the concentration of NaCl and the presence of deflocculant fluidizers, but, in general, they are corrosive, foam, affect electrical resistivity coring, and salt diminishes the effect of fluidizing additives, antifilters and emulsifiers. Initially, fluids with NaCl were used to drill through thick packages of salt and clay, but over time it was found that salty muds have a good inhibitory capacity for many categories of clays encountered during drilling.

In the practice of well drilling, fluids with NaCl are prepared in the following variants:

- unsaturated salty fluids (1 - 5 NaCl)
- semi-saturated salty fluids (10-15 NaCl)
- saturated salty fluids (>30 NaCl)

Another advantage of a NaCl-based fluid is the simplification of top-up methods.

Chapter 2: Drilling Fluid Systems and Surface Preparation

The clogging cake (consisting mainly of medium and coarse NaCl) is easy to remove by simply washing with unsaturated solutions. Another variant of the same drilling fluid is the use of specially granulated sodium chloride as a bridging material (the size of the sodium chloride granules is determined according to the size of the pores of the traversed formation).

2.2.4 Polymer-based fluids:

In general, polymers based on organic compounds are used, but also inorganic flocculants (NaCl, lime, gypsum).

The polymers can be of the cationic type, acting through their strongly positively charged hydrophilic chain, or of the anionic or nonionic type, accompanied by an electrolyte to neutralize the electrical charges of the clay plates.

From the many practical observations and laboratory studies it was found that the nature and properties of the drilling fluids greatly affect the speed of advancement of the hoe and the yardage achieved by it.

In the well, the inhibiting effect of the polymers is due to the formation of a protective film that prevents the penetration of water, swelling and dispersion of clays.

According to the functions they perform in the fluid, polymers can be classified as follows:

- complex flocculants—which flocculate both bentonite and detritus particles;
- selective flocculants—which only flocculate the drilled solids;
- flocculants with double action—which flocculate the drilled solids, but at the same time improve the yield of the bentonite.

The main disadvantage of polymer-based drilling fluids is the failure to meet the criterion of chemical solubility of system additives. The clogging cake deposited by such a drilling fluid is chemically insoluble (in acid or oxidant solutions)

2.2.5 Fluids based on petroleum products:

These fluids are dispersed systems whose continuous phase is a petroleum product, mineral oil or a synthetic fluid, in which the additives necessary to create the structure and clogging properties are dispersed and dissolved, as well as a quantity of emulsified water, added to regulate certain properties.

Chapter 2: Drilling Fluid Systems and Surface Preparation

The main variants of fluids based on petroleum products are the following:

- with low water content also called black fluids with 3-10 %water;
- inverse emulsions 10-60 %water; The specific properties of these fluids are:
- filtered reduced and consisting only of petroleum product, mineral oil or synthetic fluid;
- inertia to contaminations such as marl, clay, salt, gypsum, anhydrite, cement;
- resistance to high temperatures;
- increased stability in temperature conditions and even during long storage;
- high lubrication capacity. Due to these properties, fluids based on petroleum products/mineral oil/synthetic

fluids can be used for:

- crossing rocks with water-sensitive clay minerals, salt masses, gypsum, anhydrite, potassium salts, formations with hydrogen sulphide and carbon dioxide;
- the drilling of deep and hot wells;
- the opening of the productive layers, especially those with low pressure, because their filtrate is smaller and consists of petroleum product/mineral oil/synthetic fluid and allow, in terms of density, a drilling close to the layer-well balance;
- drilling and coring of unconsolidated sands and productive layers with clay particles;
- the reactivation of some old wells;
- release of stuck gaskets, such as packer and perforating fluids.

Establishing the emulsion involves the use of various calcium or sodium fatty acid soaps, especially naphthenic acids, as well as some metallic soaps as emulsifiers. Most of the times, the saponification of acids takes place in the emulsification process: the added fatty acids and naphthenic acids in the composition of the oil react with the calcium or sodium hydroxide dissolved in the preparation water. The calcium soap stabilizes the water-in-oil emulsion, and the sodium soap forms bonds between the two phases.

Since inverse emulsion fluids are used to solve difficult problems related to the drilling and production of productive layers, and the instability of the borehole is attributed to clay rocks and the fact that they change their properties in contact with aqueous media, inverse emulsions are made with controlled chemical activity. By regulating the activity of the aqueous phase in the

Chapter 2: Drilling Fluid Systems and Surface Preparation

reverse emulsion with electrolytes, the invasion of water into the clay rocks can be prevented and, in this way, better stability of the wellbore is ensured.

The main disadvantage of these systems when traversing the productive formations by drilling is the high potential of changing the natural humidity of the reservoir rock. In the well completion phase, washing with solvents is also needed, an operation that often leads to the formation of microemulsions and pronounced blockages of the productive formation.

2.2.6 Clear fluids:

In general, these fluids or salt solutions can be used in consolidated formations that are not affected by the penetration of large volumes of fluid into the porous permeable rock. These non-viscous fluids can be used in fractured calcareous or dolomitic formations or in formations originating from coral accumulations and sometimes, but with reservations, in fractured sandstones without interstitial clay.

These fluids require turbulent flow and viscous cleanout plugs to effectively direct the detritus out of the borehole. Viscous plugs must be made without the addition of bentonite, only based on biopolymers (xanthan gum) or HEC (hydroxyethyl cellulose).

Flocculants can be used in the surface cleaning system to keep the fluid clear and precipitate solids entrained during the drilling process. With this type of drilling fluid, completion operations are carried out in open hole or perforated liner.

2.3 The rheological properties of drilling fluids:

The rheological properties characterize the flow behavior of the drilling fluids, including the resistance to movement of some bodies in the fluid mass. These properties allow to evaluate the pressure and pumping energy of the drilling fluids, the washing conditions as well as the evacuation of the detritus, the danger of erosion of the walls.

In general, the flow behavior of fluids, but also of systems with a continuous fluid phase, is described by a series of mathematical models, which can also be called constitutive equations, flow laws or rheological models. The mathematical models express the relationship between the tangential stresses τ , which can arise between a moving fluid and the deformation (shear) velocities dv/dx , in laminar flow regime. Thus, the quantities τ and dv/dx represent the rheological variability, and the scalar parameters represent the rheological constants of the respective equations.

Chapter 2: Drilling Fluid Systems and Surface Preparation

Their values are obtained by processing the measurable quantities specific to each type of viscometer, such as, for example, flow rate and pressure drop (for tubular viscometers) or speed and tension moment (for viscometers with coaxial cylinders). Diagrams $\tau=f(dv/dx)$ are called rheograms.

- **Newtonian fluids** (their category includes water, petroleum products, electrolyte solutions and other single-phase liquids with low molar mass) have the following constitutive equation:

$$\tau = \eta_d \frac{dv}{dx} \quad (2.1)$$

The rheograms of these Newtonian fluids (are generally straight that pass through the origin, their slope itself representing the rheological constant, i.e. the so-called dynamic or absolute viscosity.

$$\operatorname{tg} \alpha = \frac{\tau}{dv/dx} \quad (2.2)$$

Having a heterogeneous structure, the drilling fluids do not obey the Newtonian flow law, and the viscosity is no longer constant. Thus, the viscosity depends on the shear rate and is called the apparent viscosity.

Drilling fluid and cement pastes can be described with sufficient precision by the following rheological models: Bingham and Ostwald de Weale. (Figure 2.1)

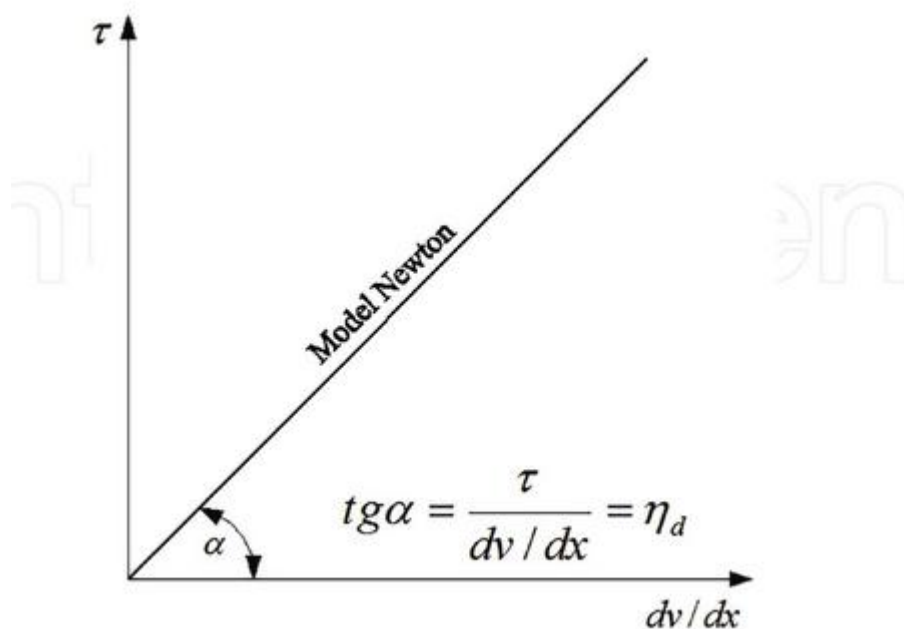


Figure 2-1: the rheograms of Newtonian fluids

Chapter 2: Drilling Fluid Systems and Surface Preparation

- **Bingham-type fluids** (which include dispersed muds with high clay content and high density, as well as poorly treated cement pastes) have the following constitutive equation:

$$T = T_0 + \eta_{pl} \frac{dv}{dx} \quad (2.3)$$

The rheograms of these fluids are straight with the origin ordinate τ_0 .

Rheograms still have and two rheological constants:

η_{pl} = plastic (structural) viscosity

τ_0 = dynamic shear stress.

Moreover, it is worth noting that η_{pl} represents the slope of the right

$$\eta_{pl} = tg \beta = \frac{T - T_0}{dv/dx} \quad (2.4)$$

and from a physical point of view, it is a measure of the internal frictions in the system, respectively between the molecules of the dispersion medium but also between its molecules and the particles of the dispersed phases, as well as the particles arranged between them.

This η_{pl} it gives indications on the total content of solids in the system.

Since τ_0 is an additional resistance, it must be overcome during the flow, to prevent the tendency of other dispersed particles in the system to form structure. In the case of drilling muds, τ_0 gives indications on the content of bentonite clay. (Figure 2.2)

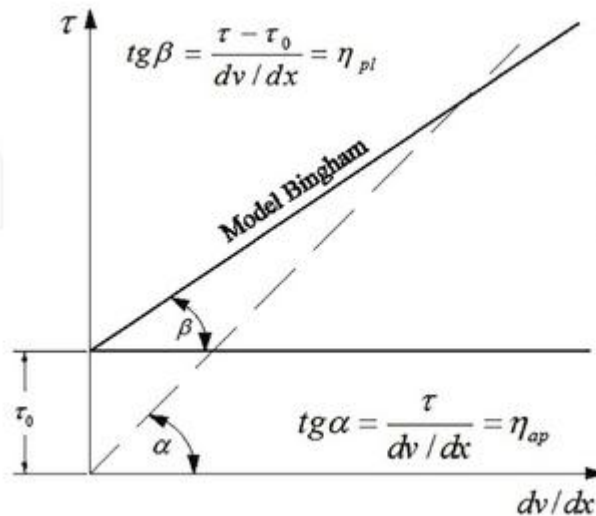


Figure 2-2 : The rheograms of Bingham fluids

2.3.1 Thixotropic properties of drilling fluids:

In general, thixotropy can be understood as the gelation of a solution when it is left at rest and the return of the gel to the solution by stirring. This phenomenon is specific to colloidal solutions, in which the dispersed particles are ionized.

Gelation usually occurs rapidly, but eventually the rate slows down, and the process often continues for several hours, days, or even months. In (Figure 2.3) are presented characteristic curves that allow the appreciation, by comparison, of the formation properties of the gel structure for some typical muds.

The static shear stress corresponding to generally very weak gels has a lower limit of $1.5\text{--}2\text{ N/m}^2$, while the upper limit, specific to strong gels, is between $15\text{--}20\text{ N/m}^2$.

Most of the drilling fluids with thixotropic properties have the ability to maintain in suspension the inert weighting materials and detritus, a characteristic that is especially necessary in case of stopping the circulation in the well. High values of thixotropy (high gels and fast gelation speeds) often cause difficulties in cleaning the drilling fluid [11-12]

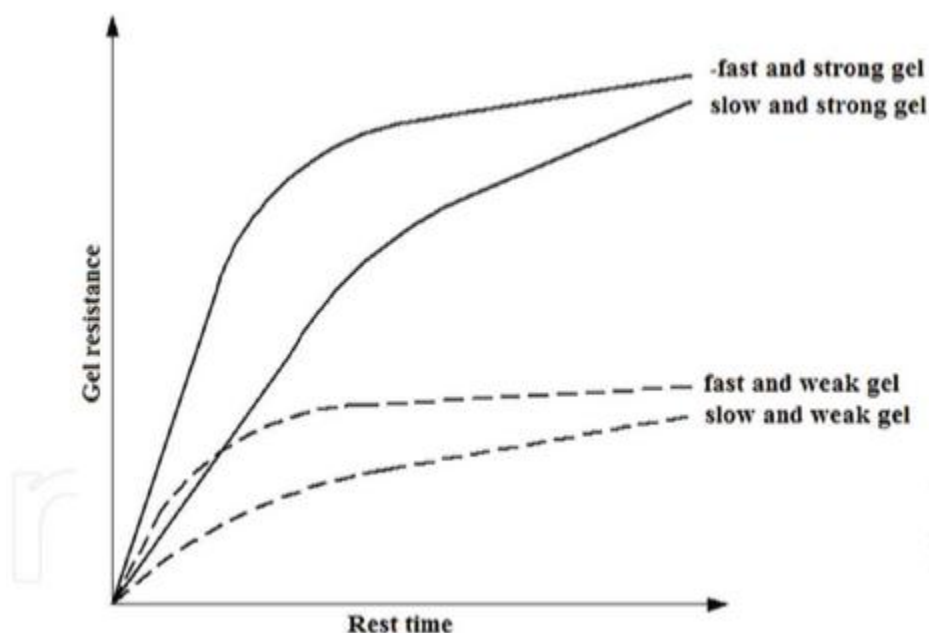


Figure 2-3: Characteristic curves of gelation of drilling fluids

2.3.1.1 Drilling Fluid Suspension and Mixing Dynamics:

The purpose of a surface mud system is to allow maintenance of the mud before it is pumped down the hole. This is accomplished by the effective use of solids-control equipment to remove undesirable solids, while simultaneously recovering as much drilling fluid as is feasible.

Secondary to the solids-removal process is the addition of chemicals and the rapid and thorough mixing of mud materials. Thorough agitation is necessary to effectively accomplish both of these tasks. In the majority of drilling fluids, agitation equipment must be used to suspend solids in the surface tanks and maintain a homogeneous drilling fluid.

There are two types of equipment to do this:

- Mechanical agitators,
- Fluid motive devices, also called mud guns.

As stated previously, the purpose of agitation equipment is to suspend solids, completely mix mud materials, and maintain a homogeneous mixture throughout the surface system.

2.3.2 The Mechanical agitators:

Mechanical agitators are used extensively for drilling-fluid surface tanks. Regardless of manufacturer, mechanical agitators have similar components, namely, a drive motor, a geared reducer (also called a gearbox), a gearbox output shaft, and impeller.

The objective of a properly designed mechanical agitation system is uniform suspension of all solids, appropriate application of shear, homogeneous fluid properties throughout the system, and economical application of applied power.

Most mechanical agitators are driven by electric motors. These motors must be rated for explosion-proof duty (to ensure that motor, starters, and wiring meet specifications for local codes and operating criteria) and may be mounted horizontally or vertically. (Figure 2.4)

Chapter 2: Drilling Fluid Systems and Surface Preparation

Motors may be coupled to or direct-face mounted to a gear reducer that in turn drives the impeller shaft. Impellers are mounted on the shaft at a specified distance off the tank bottom to achieve desired results. [8]

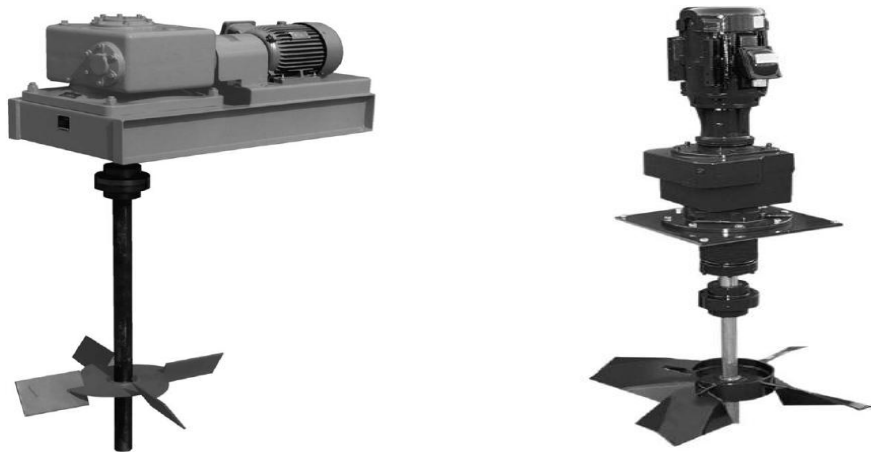


Figure 2-4: horizontally / vertically mounted unit

2.3.2.1 The Agitators Impellers:

Impellers (sometimes called turbines) convert mechanical power into fluid movement, much like the impeller of a centrifugal pump.

Every impeller transmits power to the fluid in two ways:

1. pumping ability
2. shearing ability.

Impeller design will promote one of these components by sacrificing effectiveness of the other. The amount of fluid that is moved by an impeller is its pumping capacity, or displacement capacity, and most manufacturers have undergone extensive testing to determine flow characteristics and capacities for type and size of impeller.

Shear rate should be thought of as the velocity gradient of fluid with distance. Shear rate can be measured at a point some distance from the impeller blade tips, and maximum and average values calculated. Shear stress is the product of shear rate multiplied by the

Chapter 2: Drilling Fluid Systems and Surface Preparation

viscous properties of the fluid. With Newtonian fluids in laminar flow, shear stress and shear rate are nearly synonymous. However, most drilling fluids are non-Newtonian, and therefore predictability of laboratory or paper models is less relevant to real-world applications.

When discussing agitation needs, shear rate depends on many variables, including impeller design, tip speed, distance to compartment walls, baffling, particulate concentration, particle size distribution, fluid density, plastic viscosity, gel strength, and yield point, among others. [8]

2.3.2.2 Radial Flow Impellers:

Radial flow results when the impeller blades are vertically mounted, that is, are in line with the agitator shaft. In radial flow, the impellers move fluid in a predominantly horizontal, circular pattern within the compartment. Ideally, the fluid will then travel upward once it contacts the tank wall and maintain uniform suspension throughout the compartment.

When used alone, radial-type impellers should be placed near the bottom of the tank, typically less than 12 inches (about 30 cm). For uniform agitation at both the top and the bottom of the compartment, tank depth must be limited to about 6 feet (1.83 m). When mounted higher in the tank, radial flow impellers can generate two zones of fluid movement; one above and one below the impeller. [8] (Figure 2.5)

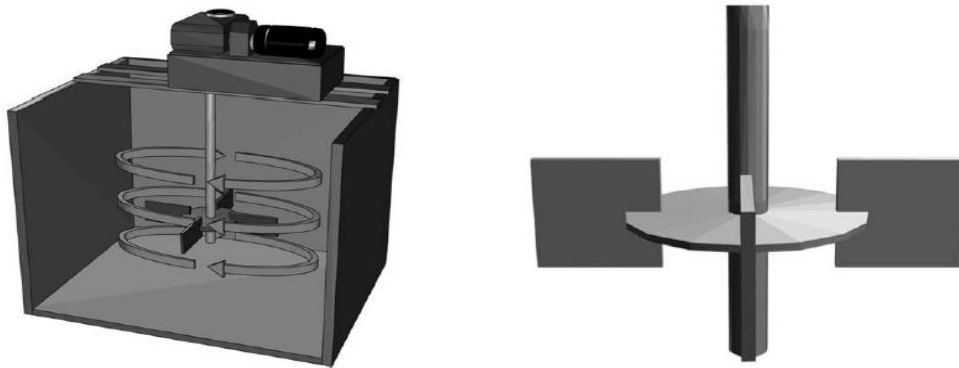


Figure 2-5: Radial Flow Impellers [12].

The upper and lower zones share a boundary with one another and therefore exhibit varying degrees of effectiveness. This scenario should be avoided and highlights the need for proper impeller placement on the shaft.

2.3.2.3 Axial Flow Impellers:

Impeller blades that are pitched at some angle toward the tank bottom, typically 45°–60° from vertical, induce a predominant axial fluid movement. The spinning motion of the blade also

Chapter 2: Drilling Fluid Systems and Surface Preparation

promotes some degree of radial flow as well. Axial flow impellers draw fluid from the compartment top along the axis of the impeller shaft and push, or “pump,” the fluid downward to the bottom, then along the bottom to the side wall, which forces the fluid upward and to the surface, where it completes the journey and begins again. When used alone, these impellers should be placed within two thirds to three quarters of the impeller diameter off bottom. Fluid also travels in a radial pattern within the compartment, due to spinning of the impeller. The combination of both radial and axial motion induces more thorough mixing in most instances. Tanks deeper than 6 feet (1.83 m) will require some type of axial flow impeller and may require more than one impeller per shaft. [8] (Figure 2.6)

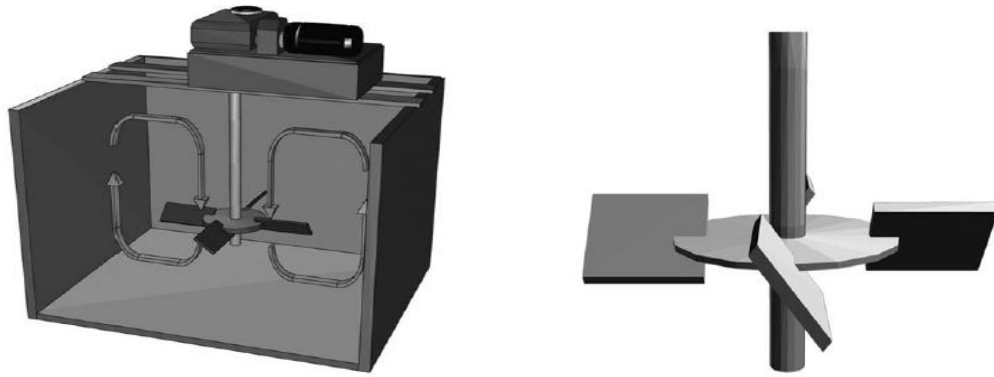


Figure 2-6: Axial Flow Impellers [12].

Most axial flow impellers have a constant blade angle. This produces more flow at the blade tip and less toward the hub. These types of impellers pump less, but induce more shearing force.

2.4 Conclusion:

In summary, this chapter has established the fundamental relationship between the chemical composition of drilling fluids and their physical behavior during surface operations. By defining drilling mud as a complex multiphase suspension, we have identified that its effectiveness depends heavily on maintaining specific rheological properties, whether behaving as a Newtonian fluid or following the Bingham plastic model.

Chapter 2: Drilling Fluid Systems and Surface Preparation

The transition from theoretical rheology to the practical requirements of solid-liquid suspension highlights a critical challenge: the natural tendency of granular particles, such as sand, to settle out of the base fluid. Overcoming this settling velocity requires a precise understanding of mixing dynamics by identifying the right agitator.

The primary goal of this study is to understand exactly how the solid phase flows within a specific type of agitator. By analyzing these flow patterns, we can ensure that the mechanical energy is sufficient to keep the sand in suspension. Ultimately, these principles provide the essential framework for the next stage of this study, where Ansys Fluent will be used to numerically simulate and optimize these complex interactions within a virtual environment

Chapter3: NUMERICAL MODELING AND SIMULATION SETUP

3.1 Introduction

This chapter presents the numerical methodology used to analyze the solid–liquid mixing process inside a mechanically stirred tank. The study focuses on the main hydrodynamic parameters governing the suspension of sand particles, including the velocity field, pressure distribution, turbulent kinetic energy (k), turbulence dissipation rate (ε), and sand volume fraction. These parameters are used to evaluate fluid circulation, turbulence intensity, particle transport, and mixing efficiency. The simulation is performed using ANSYS Fluent to provide a better understanding of the interaction between the liquid and solid phases under mechanical agitation.

3.2 Physical and geometrical description

3.2.1 Initial Geometrical Representation

The Figure 3.1 shows a sketch of the stirred tank in the YZ plane, including the impellers and the tank geometry. This sketch represents the first step of the project and serves as the basis for the mesh generation process this was the main idea and how it's started.

The preparation of the geometrical model represents the first and one of the most important stages of the numerical simulation. Since the objective of this study is to analyze the suspension and distribution of sand particles inside a mechanically stirred tank, the computational domain must accurately reproduce the main features of the real mixing system. An appropriate geometric representation ensures that the numerical model can realistically simulate the interaction between the rotating impellers, the liquid phase, and the solid particles.

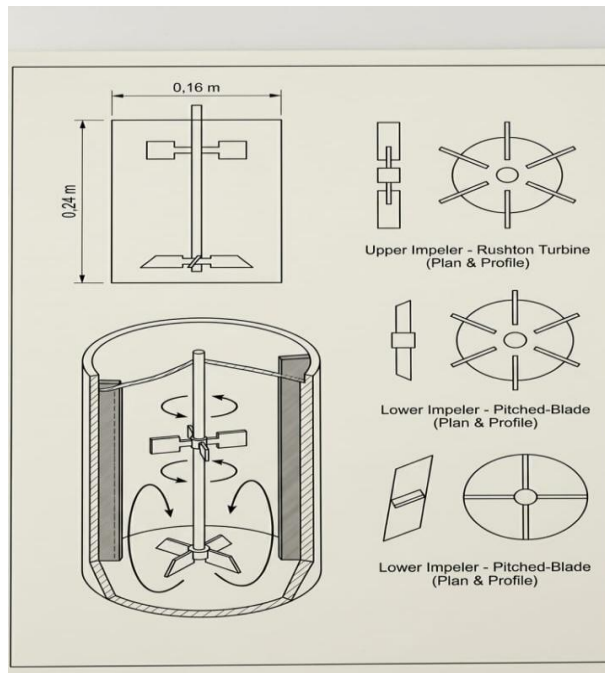


Figure 3-1: equipment sketch

3.2.2 Geometrical modeling and meshing

The studied system consists of a **three-dimensional mixing tank** equipped with:

- A cylindrique vessel (figure 3.2)
- Two rotating impellers mounted on a central shaft (figure 3.3)
- Internal elements such as baffles and a sparger

The geometry used in this study consists of a three-dimensional stirred tank with approximate dimensions of:

- Tank **diameter**: 0.16 m
- Tank **height**: 0.24 m
- Impeller diameter: 0.07m
- Impeller diameter: 0.05m
- Shaft: 0.021m

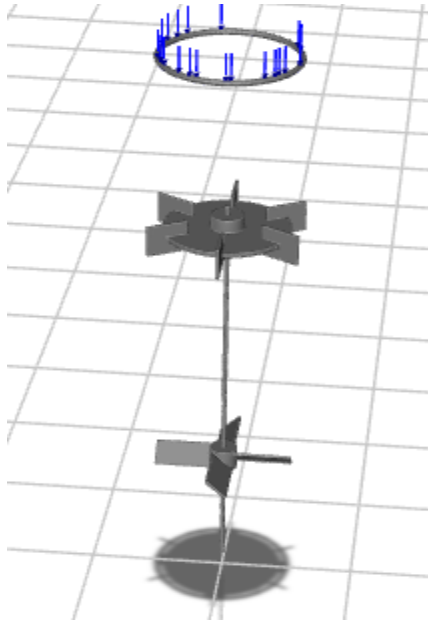


Figure 3-3: rotating blades and runny int

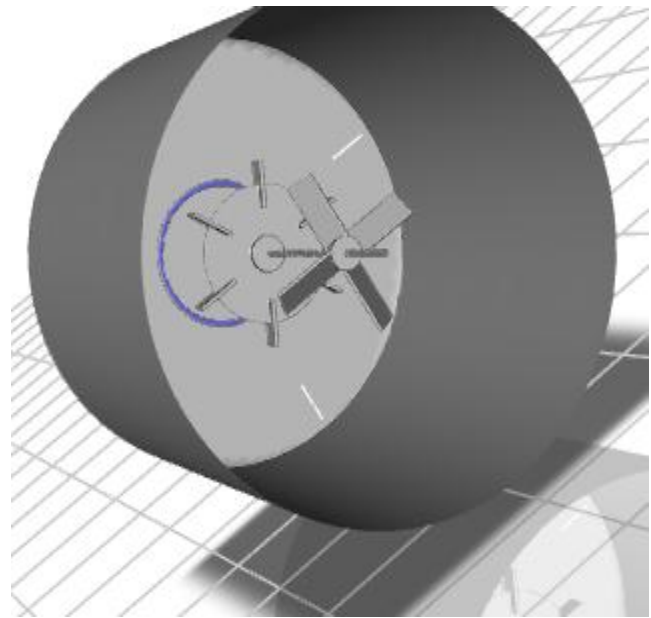


Figure 3-2: tank body with internal equipment

Assumptions:

- The flow is turbulent
- The movement is radial and axial
- Water as the primary phase and sand as the granular secondary phase.

3.2.2.1 Boundary:

Boundary conditions were defined to reproduce the operating conditions of the stirred tank. No-slip conditions were applied at the tank walls, while the impeller region was assigned rotational motion to induce fluid circulation and promote solid–liquid mixing.

Gravity was included to represent the settling behavior of the sand particles, while the interaction between the liquid and solid phases was modeled using the Eulerian-Eulerian approach coupled with the Gidaspow drag model. These boundary conditions were selected to reproduce the actual operating conditions and ensure a realistic prediction of the flow field, turbulence, and particle suspension characteristics within the mixing tank.

`fluid_mfr_1-1` and `fluid_mfr_2-0`: rotating regions around the impellers

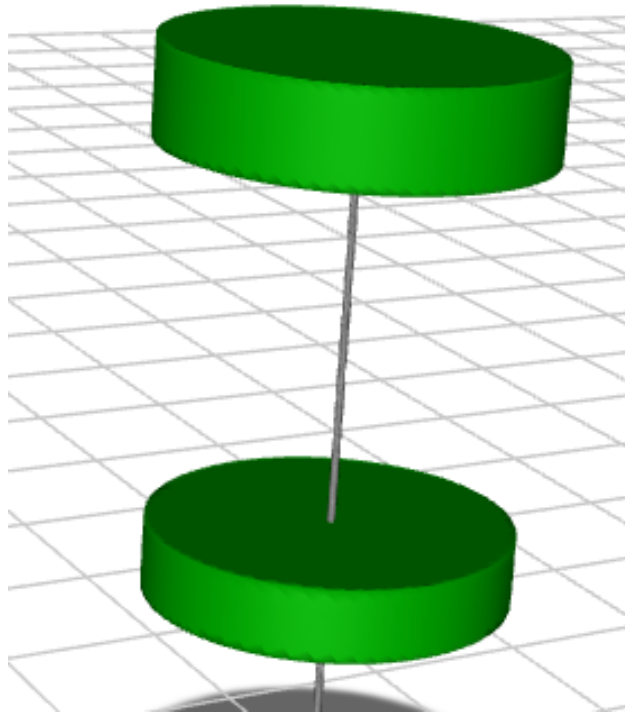


Figure 3-4: `fluid_mrf_1-1` and `fluid_mrf_2-0`

3.2.2.2 Meshing

The computational domain was discretized into a finite number of control volumes to enable the numerical solution of the governing equations. An appropriate mesh was generated using ANSYS Meshing, ensuring an adequate representation of the tank geometry and the impeller regions. Particular attention was given to the zones surrounding the impellers, where finer elements were employed to accurately capture the complex flow structures and the strong velocity gradients induced by the rotating blades. A coarser mesh was adopted in regions characterized by lower flow variations in order to optimize computational efficiency.

The resulting mesh provides a satisfactory compromise between numerical accuracy and computational cost, thereby ensuring reliable predictions of the hydrodynamic behavior and particle suspension within the stirred tank. (Figure 3.4)

Chapter 3: Numerical Modeling and Simulation Setup

The mesh is designed to capture:

- Flow gradients near the impellers
- Interaction between rotating and stationary regions
- Overall fluid circulation within the tank

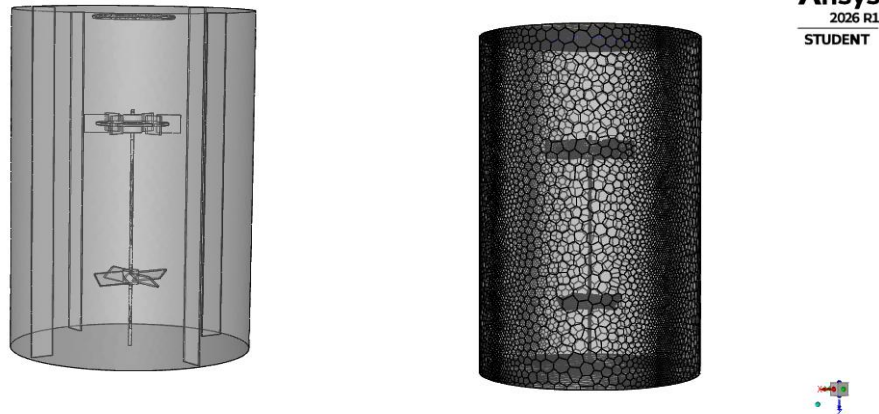


Figure 3-5 full tank and impellers mesh

Special attention was devoted to the meshing of the impeller region due to its significant influence on the flow dynamics and mixing performance. A finer mesh was employed around the impeller blades and within the rotating zones to accurately capture the strong velocity gradients, turbulence generation, and complex flow patterns induced by the impeller motion (Figure 3.5). This local mesh refinement enhances the resolution of the fluid-solid interactions and improves the prediction of particle suspension and circulation within the tank. In contrast, relatively coarser elements were used in regions farther from

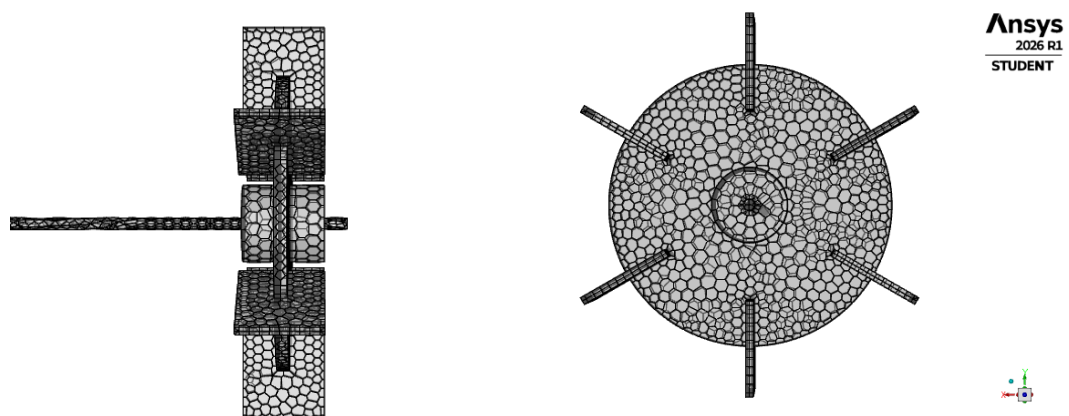


Figure 3-6 : upper impeller mesh

Chapter 3: Numerical Modeling and Simulation Setup

the impellers to reduce the computational cost while maintaining satisfactory numerical accuracy. (Figure 3.6) (Figure 3.7)

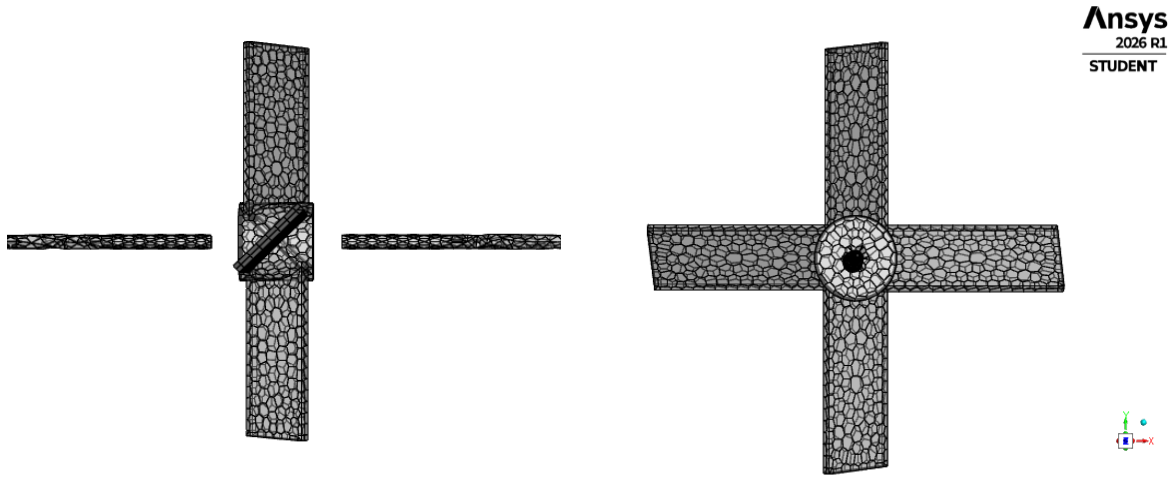


Figure 3-7: lower impeller mesh

Table 3-1: table of mesh conditions

Parameter	Value
Tank Diameter	0.16 m
Tank Height	0.24 m
Total Domain Volume	$4.793 \times 10^{-3} \text{ m}^3$
Minimum Cell Volume	$7.62 \times 10^{-12} \text{ m}^3$
Maximum Cell Volume	$5.26 \times 10^{-7} \text{ m}^3$
Minimum Orthogonal Quality	0.604
Nodes	1093547
Faces	1373796

3.3 Physical Models

3.3.1 Gravity Effect:

Gravity is activated in the negative vertical direction: $g = 9.84 \text{ m/s}^2$

Chapter 3: Numerical Modeling and Simulation Setup

This parameter is essential to reproduce the natural tendency of sand particles to settle at the bottom of the tank. It also plays a crucial role in evaluating the efficiency of mixing, as it opposes particle suspension.

3.3.2 Multi-phase Model:

The **Eulerian multiphase model** is selected to simulate the interaction between water and sand. In this approach, both phases are treated as interpenetrating continua, allowing the solver to account for:

- Momentum exchange between phases
- High particle concentration
- Granular behavior of solid particles

3.3.3 Turbulence Modeling

The flows inside the tank are highly turbulent due to impeller rotation. Therefore, the standard k -epsilon (2eqn) with turbulence multiphase model is employed.

This model is widely used in industrial applications because it:

- Provides stable solutions
- Accurately predicts general flow behavior
- Handles recirculation and mixing phenomena efficiently

3.4 Material Properties

The physical properties of each phase are defined as follows:

3.4.1 Water (Primary Phase):

- Density: 998.2 kg/m³
- Dynamic viscosity: standard value

3.4.2 Sand (Secondary Phase)

- Density: 2650 kg/m³

Chapter 3: Numerical Modeling and Simulation Setup

- Particle diameter: 0.000111 m
- Granular option: activated

The granular model allows better representation of particle interactions and packing behavior, especially at high concentrations with some modification in:

Angular Visco - Granular bulk – packing limit.

3.5 Cell Zone Conditions and Rotational Modeling

To simulate the impeller motion, the **MRF approach** is applied:

- The regions **fluid_mfr_1-1** and **fluid_mfr_2-0** are assigned a rotational speed of **450 rpm**
- The main tank region **fluid_tank-2** remains stationary

This approach enables a steady representation of rotational effects without the complexity of dynamic mesh methods.

The high-speed shows how the blades move the sand around and how the mixture mix

The rotation generates:

- Strong velocity gradients
- Shear forces
- Recirculation zones

3.6 Initialization and Phase Distribution

3.6.1 Initialization Strategy

A hybrid initialization to create a realistic, non-uniform initial flow field and ensure full control over phase distribution. This step sets:

- Water volume fraction = 1
- Sand volume fraction = 0

Chapter 3: Numerical Modeling and Simulation Setup

throughout the entire domain so water situated in all the tank and eliminate the sad existence (initial experience) to avoid the wrong distribution of sand in the fluid. This clean initial condition avoids numerical instabilities and unwanted phase presence.

3.6.2 Sand Injection Using Patch

To ensure that Sand is initially concentrated in the lower region of the tank and that no artificial accumulation occurs near the impellers we must patch the sand phase manually to

- In the main tank (fluid_tank-2): $\rightarrow$ sand volume fraction = 0.56
- In the rotating regions (fluid_mfr_1-1, fluid_mfr_2-0): $\rightarrow$ sand volume fraction = 0

3.7 Boundary conditions

Adjusting all the wall boundary a stationary wall motion and a standard roughness where the sand grain roughness height is 0 and constant at 0.5.

Both impellers and shafts are moving with same speed of 450 m/s.

3.8 User-Defined Function (UDF) Implementation

In order to improve the accuracy of the simulation and better control the physical behavior of the system, a User-Defined Function (UDF) was implemented using a C file (fix.c).

The purpose of this UDF is to define specific conditions that are not directly available in the standard Fluent models, particularly related to phase distribution and flow behavior.

The UDF allows direct access to the solver variables and enables the modification of certain parameters during the simulation.

3.8.1 Mathematical Formulation

In this study, a three-dimensional Eulerian two-fluid model is used to simulate the solid–liquid flow inside the stirred tank. In this approach, water and sand are treated as two continuous phases that exist together inside the domain.

Chapter 3: Numerical Modeling and Simulation Setup

The Eulerian model is suitable for this type of simulation because it can represent particle movement, suspension, and interaction between phases.

The sum of all phase volume fractions is given by:

$$\alpha_l + \alpha_s = 1 \quad (3.1)$$

where:

- $\alpha_l \rightarrow$ liquid volume fraction
- $\alpha_s \rightarrow$ solid volume fraction

Continuity Equation

The mass conservation equation for each phase is written as:

$$\frac{\partial}{\partial t}(\alpha\rho) + \nabla \cdot (\alpha\rho\vec{v}) = 0 \quad (3.2)$$

This equation describes the conservation of mass during the flow.

• Momentum Equation

The momentum equation is expressed as:

$$\frac{\partial}{\partial t}(\alpha\rho\vec{v}) + \nabla \cdot (\alpha\rho\vec{v}\vec{v}) = -\alpha\nabla p + \alpha\rho g \quad (3.3)$$

This equation represents the movement of the phases under the effect of pressure, gravity, and fluid motion.

• Turbulence Model

The standard $k - \epsilon$ turbulence model is used to describe turbulence inside the tank.

The turbulent viscosity is calculated using:

Chapter 3: Numerical Modeling and Simulation Setup

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3.4)$$

where:

- $k \rightarrow$ turbulent kinetic energy
- $\varepsilon \rightarrow$ turbulence dissipation rate

This model helps predict turbulence generated by the rotating impellers and improves the representation of the mixing process.

The implemented function is based on the following principle:

$$\phi_{sand} = f(x, y, z)$$

where:

- ϕ_{sand} represents the sand volume fraction
- x, y, z are the spatial coordinates

In this work, the function is used to control the spatial distribution of sand, ensuring that it is initially located in the lower region of the tank.

In practical terms, the UDF applies a condition such as:

$$\phi_{sand} = \begin{cases} \phi_0, & \text{if } z < z_{limit} \\ 0, & \text{if } z \geq z_{limit} \end{cases} \quad (3.5)$$

This ensures that sand is present only in the bottom part of the tank at the beginning of the simulation.

The Eulerian two-fluid model provides a good representation of the interaction between water and sand inside the stirred tank. It allows the simulation of particle suspension, sedimentation, and turbulent mixing during the stirring process.

- **Reynolds Number (Re):**

Chapter 3: Numerical Modeling and Simulation Setup

The Reynolds number (Re) is used to determine if a flow is laminar or turbulent. It is a dimensionless number that compares the inertial force with the viscous force. Inertial forces are proportional to a body's mass and velocity

$$Re = \frac{\rho V D}{\mu} \quad (3.6)$$

Where:

ρ : Fluid density V: Velocity

D: Characteristic length (e.g., pipe diameter)

μ : Dynamic viscosity (for Newtonian fluids)

The generally accepted value of the Reynolds number above which stable laminar flow no longer occurs is:

- Laminar: $Re < 2000$
- Transitional: $2000 < Re < 4000$
- Turbulent: $Re > 4000$

At the termination of the laminar flow, and before the turbulent flow begins, there is a transition zone in which the flow is irregular, and the pressures in the fluid are highly unstable.

Since pressure losses increase rapidly in turbulent flow, turbulent-flow equations should be used (for the sake of safety) as soon as laminar flow has ceased.

For time-independent fluids, the critical value of the Reynolds number depends upon the type and the degree of non-Newtonian behavior.

The Reynolds number for a non-Newtonian fluid, also called the equivalent Reynolds number. Reynolds number for the Bingham fluid is defined as:

$$Re = \frac{v^2 D P}{\tau_0 D + 8 V \mu_p} \quad (3.7)$$

3.8.2 Role of the UDF in the Simulation

The use of the UDF provides several advantages:

- It ensures a realistic initial distribution of sand
- It avoids non-physical placement of particles near the impellers
- It improves the stability of the simulation
- It gives better control over the initial conditions

Discussion

Without the use of the UDF, the initialization of the sand phase may lead to incorrect distributions, such as particles appearing near the blades or in regions where they should not exist physically.

By using the UDF, the simulation starts from a more realistic state, which leads to more reliable and meaningful results.

3.9 The calculation parameters

3.9.1 Relaxation Factors

To enhance stability:

- Pressure: 0.3
- Momentum: 0.5
- Volume fraction: 0.2
- Turbulence quantities: 0.5

3.9.2 Numerical Parameters

The simulation is performed under transient conditions using the following parameters:

- Time step: 0.005 s
- Number of time steps: 200

Chapter 3: Numerical Modeling and Simulation Setup

- Iterations per time step: 40

The document was recorded after every step

Chapter4: Results And Discussion

4.1 Introduction

This chapter presents the results obtained from the numerical simulation of the solid–liquid mixing process inside the stirred tank. The analysis is based on two complementary elements: the residual evolution, which reflects the numerical behavior of the solver, and the contour plots, which show the physical evolution of the sand–water mixture inside the tank.

To obtain a clearer understanding of the process, the results are examined at different time steps, especially every 10 steps, using both the YZ plane and the lower blade region. This approach makes it possible to follow the mixing process from the initial state to the developed transient regime and to evaluate the influence of impeller rotation on particle suspension and dispersion.

4.2 Residual Analysis and Numerical Behavior

At the beginning of the simulation, the residuals exhibit very high values. This behavior is expected because the initial condition represents a simplified and non-physical state where the flow is not yet developed.

During the first iterations, a sharp decrease in residuals is observed. This indicates that the solver is successfully establishing the velocity field, pressure distribution, and turbulence structure.

As the simulation progresses, the residuals display a periodic oscillatory behavior, forming a characteristic zig-zag pattern. This pattern is directly linked to the transient nature of the simulation:

- At the beginning of each time step, the equations are updated → residuals increase
- During iterations, the solution stabilizes → residuals decrease

The regularity of this pattern confirms that the simulation is stable and that the selected time step is appropriate. Unlike steady-state simulations, a perfectly flat residual curve is not expected here.

4.3 Evolution of the Mixing Process

4.3.1 Initial State (Step 0 – Step 10)

At the very beginning of the simulation, the system is characterized by a completely stratified configuration in which the sand particles are entirely concentrated at the bottom of the tank, forming a dense and compact layer, while the water phase occupies the upper region without any visible interaction between the two phases. This situation reflects a purely gravity-dominated regime, where the solid particles remain at rest due to their higher density compared to the fluid. (Figure 4.1)

At this stage, the velocity field is almost negligible throughout the domain (Figure 4.2), as the impellers have not yet transferred sufficient mechanical energy to the fluid. Consequently, no meaningful mixing occurs, and the interface between the sand and water remains clearly defined



Figure 4-2: sand water distribution in tank

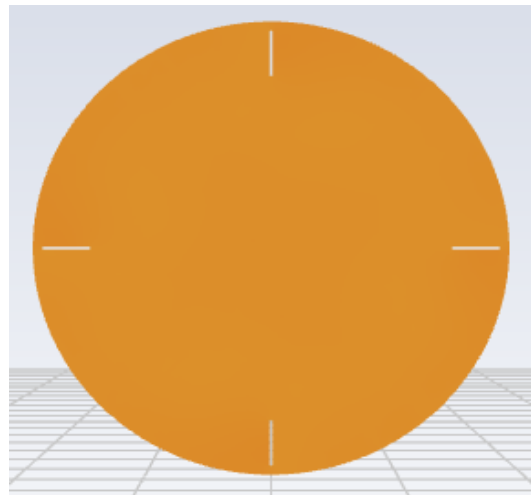


Figure 4-1 sand distribution in bottom of tank

and stable. This initial condition serves as a reference state from which the entire mixing process begins to evolve

Chapter 4: Results And Discussion

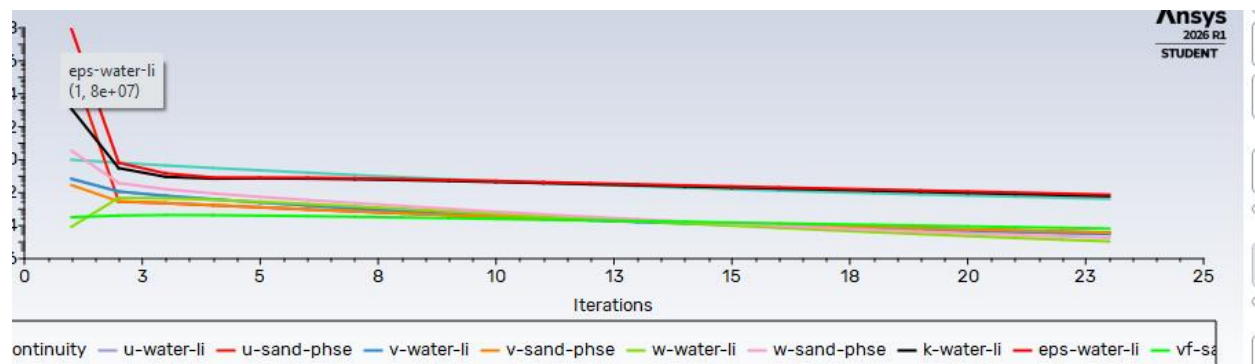


Figure 4-3: Graph of variables at the first iterations

At the initial stage, the system is clearly stratified:

- Sand is fully concentrated at the bottom
- Water occupies the upper region
- The flow is almost negligible

This stage represents the reference condition before mixing begins. At this point, gravity dominates the system, and no mixing is observed. The impellers have not yet transferred enough energy to the fluid to affect particle distribution. (Figure 4.3)

4.3.2 Early Stage (Step 10 – Step 40)

As the impellers start rotating:

- Flow begins to develop near the blades
- Small circulation zones appear
- Sand particles start to move slightly

However, the majority of particles remain near the bottom.

As the simulation progresses and the impellers begin to rotate, the flow field starts to develop gradually, particularly in the regions close to the blades where the mechanical energy is first introduced into the system. The motion of the fluid generates localized velocity gradients, which lead to the formation of small circulation zones around the impellers. (Figure 4.2)

Chapter 4: Results And Discussion

During this stage, the effect of the hydrodynamic forces becomes noticeable, although still limited in magnitude. A slight displacement of sand particles can be observed, especially in the vicinity of the rotating elements, where the fluid motion is more intense. However, the majority of the particles remain concentrated near the bottom, indicating that gravitational forces are still dominant over the fluid-induced forces. (Figure 4.3)

Compared to the initial state, this stage marks the transition from a completely static system to a weakly dynamic one, where the first interactions between phases begin to appear.

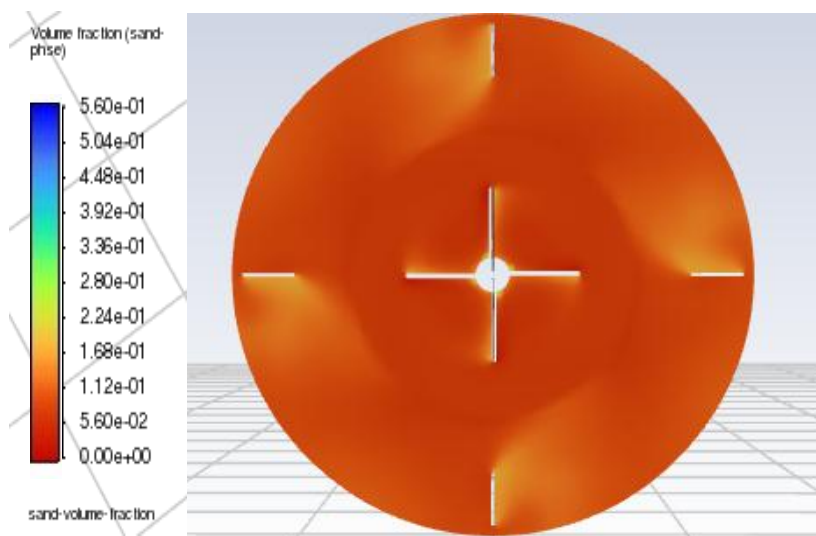


Figure 4-5 volume fraction of sand on the lower blade



Figure 4-4 volume fraction of sand on YZ view

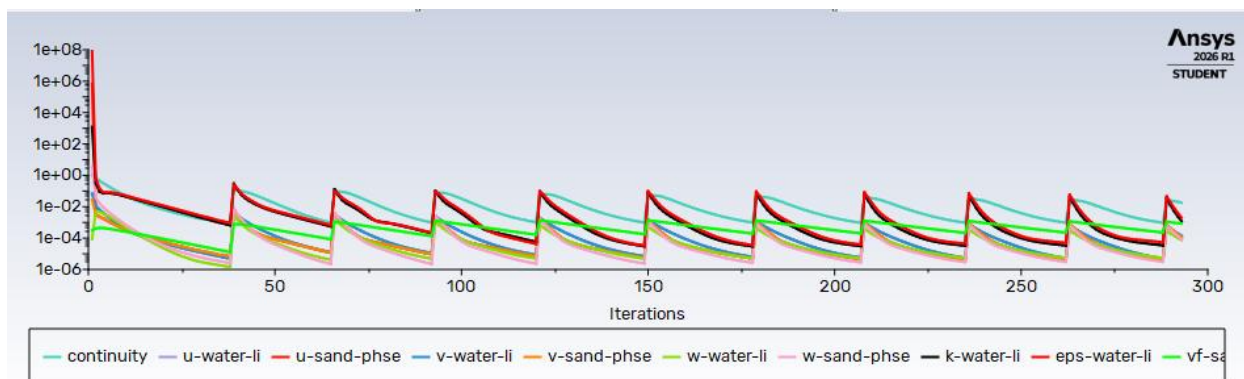


Figure 4-6: Evolution of scaled residuals transient simulation showing periodic convergence behavior associated with time stepping (from 0 to 300 iterations)

Chapter 4: Results And Discussion

The residual curve presented in this figure shows the evolution of the scaled residuals over successive iterations during the transient simulation. Unlike a steady-state simulation, the behavior observed here is characterized by a clear and repetitive oscillatory pattern, which is a direct consequence of the transient formulation adopted in this study. (Figure 4.4)

More precisely, the residuals exhibit a periodic “saw-tooth” or zig-zag shape, where each peak corresponds to the beginning of a new time step. At this moment, the governing equations are updated, leading to a temporary increase in the residual values. This increase is immediately

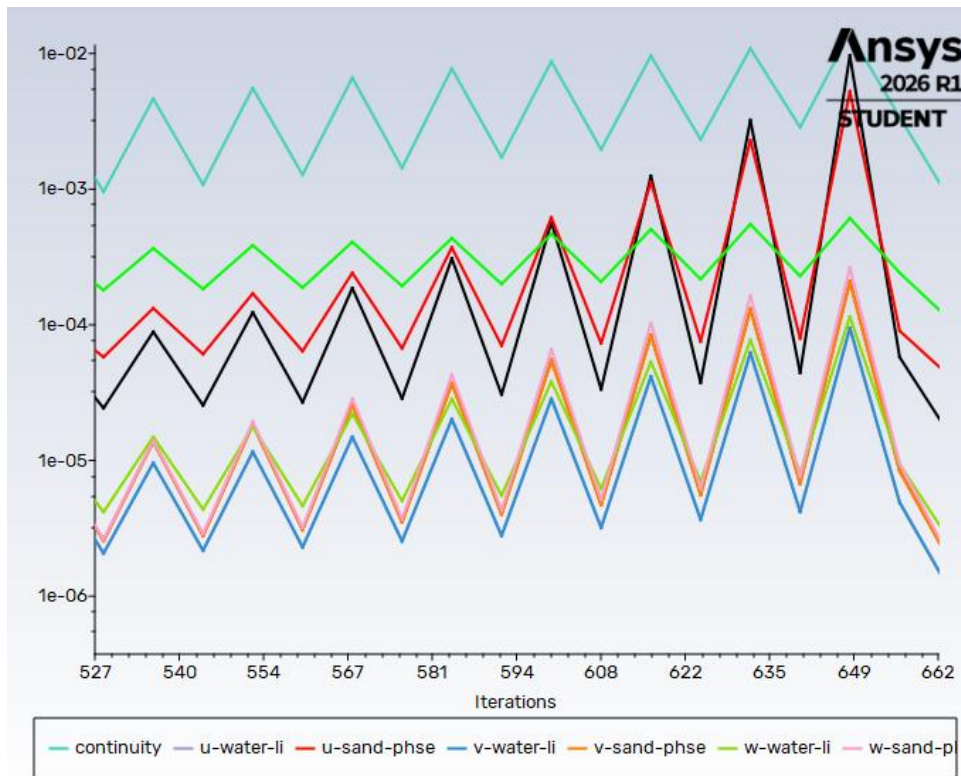


Figure 4-7 Evolution of scaled residuals during transient simulation showing periodic convergence behavior associated with time stepping (from 525 to 650)

followed by a gradual decrease as the solver iterates within the same time step to reach convergence.

It can also be observed that the amplitude of these oscillations slightly increases over time, particularly for the continuity and velocity residuals. This behavior indicates that the flow is becoming more complex and more energetic as the mixing process develops. Indeed, as the

Chapter 4: Results And Discussion

impellers continue to rotate, turbulence intensity increases, and the interaction between the water and sand phases becomes stronger, which naturally makes convergence more challenging. (Figure 4.5)

Despite these oscillations, the residuals remain within acceptable limits, generally ranging between 10^{-3} and 10^{-6} for most variables. This confirms that the simulation maintains numerical stability throughout the computation. The absence of divergence or uncontrolled growth in the residuals further indicates that the selected numerical parameters, including the time step and relaxation factors, are appropriate.

Another important observation is that the sand-phase residuals tend to fluctuate more than those of the water phase. This is expected due to the additional complexity introduced by the granular behavior and the strong coupling between phases. The presence of particles introduces non-linear interactions, which are reflected in the residual evolution.

Overall, this residual pattern is characteristic of a well-behaved transient multiphase simulation. Rather than indicating instability, the oscillatory behavior confirms that the solver is correctly capturing the time-dependent dynamics of the mixing process. Therefore, the results obtained from this simulation can be considered reliable and physically meaningful.

4.3.3 Intermediate Stage (Step 40 – Step 100)

At this stage, the mixing process becomes significantly more pronounced as the flow field develops into a more structured and energetic configuration. The continuous rotation of the impellers generates strong circulation loops that extend throughout a larger portion of the tank, enhancing the transport of momentum within the fluid. (Figure 4.6)

As a result, the sand particles begin to detach more clearly from the bottom layer and are progressively carried upward by the fluid motion. The competition between gravitational settling and hydrodynamic lifting forces becomes evident, as some particles are suspended while others still tend to fall back toward the bottom. (Figure 4.7)

Chapter 4: Results And Discussion

This stage represents a critical phase in the mixing process, where the system transitions from localized motion near the blades to a more global circulation pattern affecting the entire

Tank (Figure 4.8).

The distribution of sand becomes less uniform and more dynamic, indicating the onset of effective mixing.

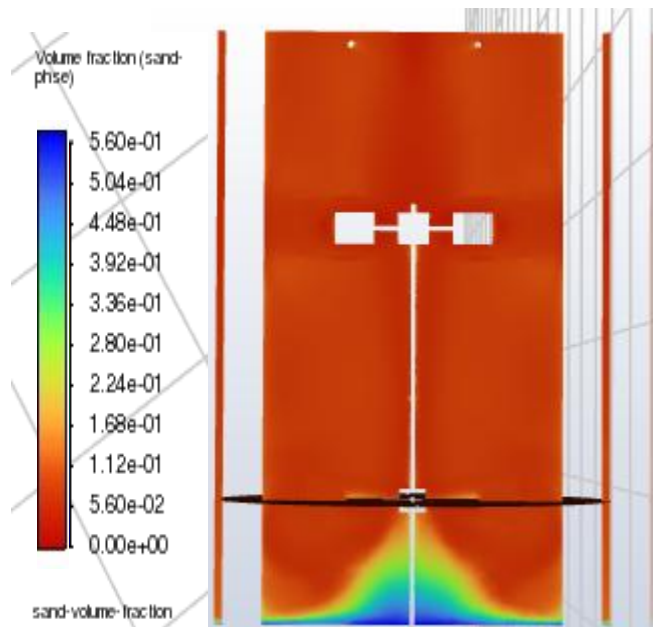


Figure 4-9 volume fraction on YZ view

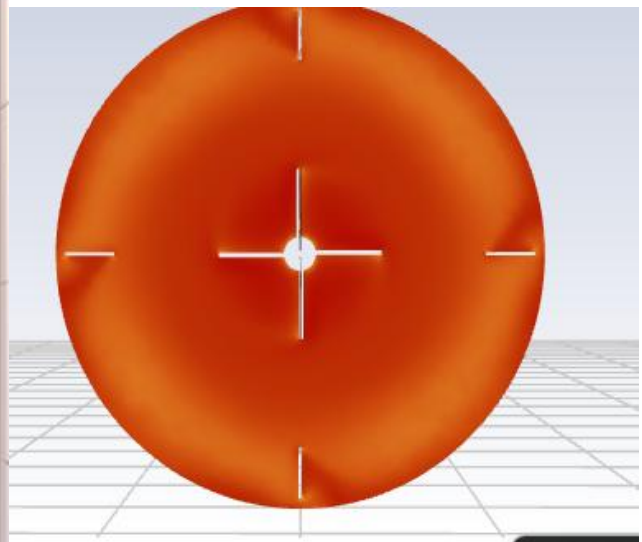


Figure 4-8 volume fraction on lower blade

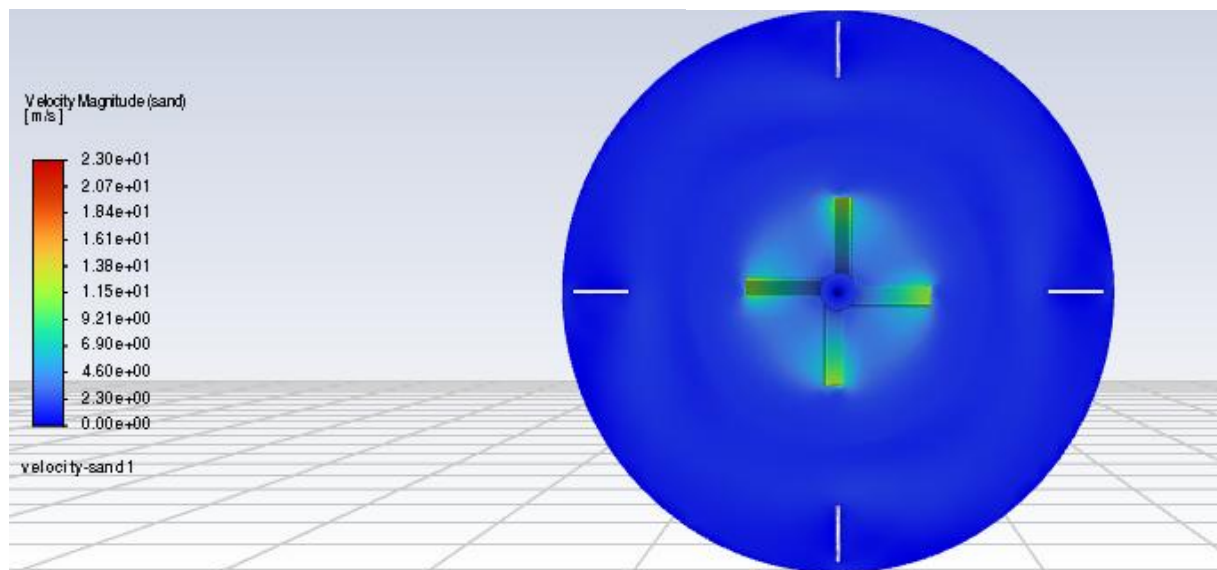


Figure 4-10: sand velocity on lower blade

Chapter 4: Results And Discussion

This stage can therefore be considered as the onset of effective mixing, where the system transitions from a predominantly gravitational regime to a turbulence-driven regime

the mixing process becomes more visible:

- Strong circulation loops are formed
- Velocity increases significantly near the impellers
- Sand particles are lifted from the bottom

The interaction between gravity and turbulence becomes clearly noticeable.

A more focused analysis of the residual evolution between steps 40 and 100 reveals important insights into the development of the mixing process. In this interval, the residual curves exhibit a noticeable increase in oscillation amplitude compared to the earlier stages of the simulation.

During this phase, the periodic saw-tooth pattern becomes more pronounced, with higher peaks observed at the beginning of each time step. This behavior indicates that the solver is dealing with a more complex and dynamic flow field, as the system transitions from weak initial motion to a more developed mixing regime. (Figure 4.9)

In particular, the residuals associated with the sand phase show stronger fluctuations than those of the water phase. This can be explained by the increasing interaction between the solid and liquid phases, as sand particles begin to detach from the bottom and enter the main flow. The onset of particle suspension introduces additional non-linearities into the system, which are reflected in the convergence behavior.

Furthermore, the continuity residual also shows relatively higher values in this region, suggesting that mass conservation becomes more challenging as the flow structures intensify. This is consistent with the formation of recirculation zones and localized turbulence generated by the impellers.

Compared to the earlier stage (step 0–40), where the residuals were decreasing smoothly and the flow remained relatively simple, the interval between steps 40 and 100 represents a clear transition toward a more active and physically complex regime. The increase in residual oscillations is

Chapter 4: Results And Discussion

therefore not a sign of instability, but rather an indication that the mixing process is becoming more effective.

Despite these larger fluctuations, the residuals remain bounded within acceptable limits, and no divergence is observed. This confirms that the numerical setup remains stable even as the physical complexity of the system increases.

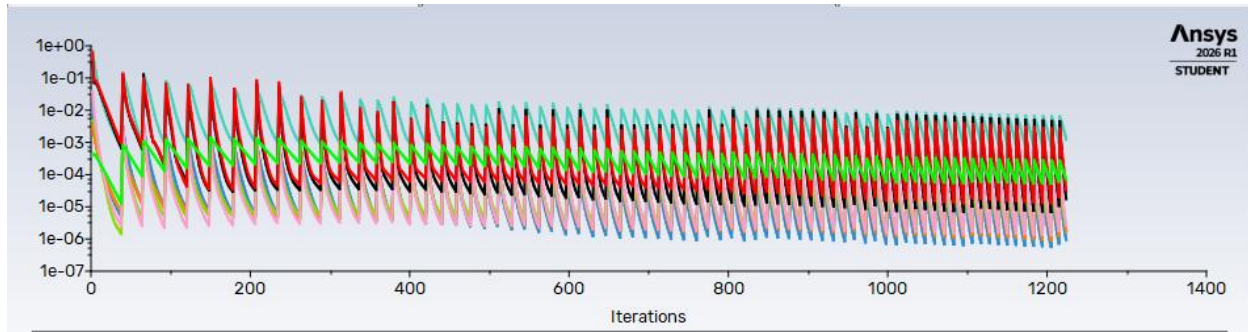


Figure 4-11: evolution of scaled residuals showing convergence behavior in multiphase mixing

Comparison with Early Stage (0–40)

Compared to the initial stage, where the residuals showed a rapid decrease followed by relatively small oscillations, the behavior observed between steps 40 and 100 reflects a clear increase in flow activity. While the early stage was dominated by flow establishment and weak particle motion, this intermediate phase is characterized by the development of strong hydrodynamic interactions and the beginning of effective particle transport.

4.3.4 evolution of scaled residuals showing convergence behavior in multiphase mixing:

With further progression of the simulation, the mixing process reaches a more advanced level characterized by a significant expansion of the region occupied by sand particles. The recirculation zones generated by the impellers become fully developed and more stable, allowing for continuous transport and redistribution of particles within the tank. (Figure 4.10)

At this stage, the influence of turbulence becomes dominant, as the energy introduced by the impellers is sufficient to overcome gravitational forces for a large portion of the particles. The sand

Chapter 4: Results And Discussion

is no longer confined to the lower region but is instead dispersed across a substantial volume of the fluid. (Figure 4.11)

Compared to the intermediate stage, the system exhibits a more organized flow structure, with well-defined circulation patterns that contribute to maintaining the particles in suspension. The mixing process becomes more efficient, although complete homogeneity is not yet achieved.

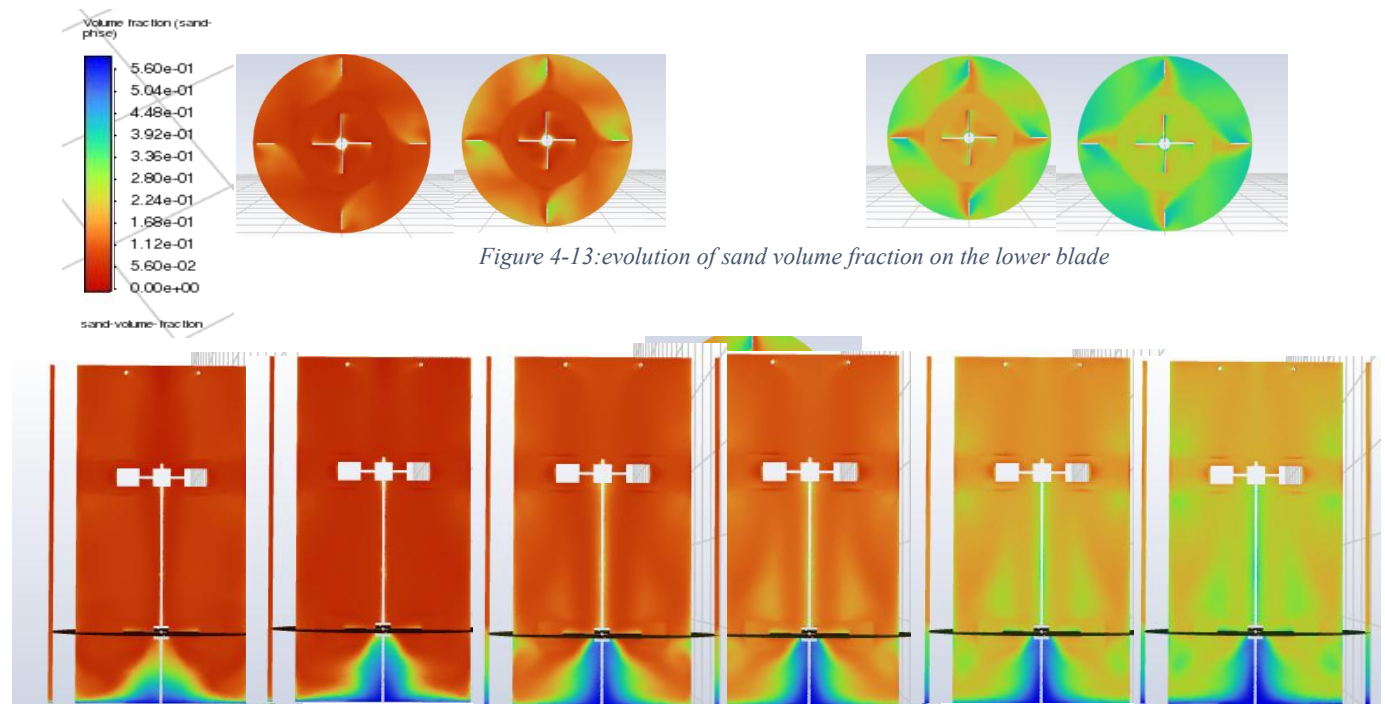


Figure 4-12 evolution of sand volume fraction on YZ view

As time progresses:

- Sand is distributed across a larger volume
- Recirculation zones are fully developed
- The flow becomes more structured

The impellers now generate sufficient turbulence to maintain particle motion.

4.3.5 Velocity Interpretation

The velocity contours in the YZ plane illustrate the distribution of fluid motion inside the stirred tank during the mixing process.

The highest velocity values are observed near the impeller blades, where the rotation transfers mechanical energy directly to the fluid. These high-velocity regions indicate strong fluid acceleration and intense circulation generated by the impellers. (Figure 4.12)

As the fluid moves away from the blades, the velocity gradually decreases due to viscous dissipation and energy loss. Lower velocity regions are mainly observed near the tank walls and at the bottom of the tank.

The contours also reveal the formation of circulation loops inside the tank. These recirculation zones play an important role in transporting sand particles and improving mixing efficiency.

The comparison between velocity contours and sand distribution confirms that regions with higher velocity correspond to stronger particle suspension, while low-velocity regions favor sedimentation.

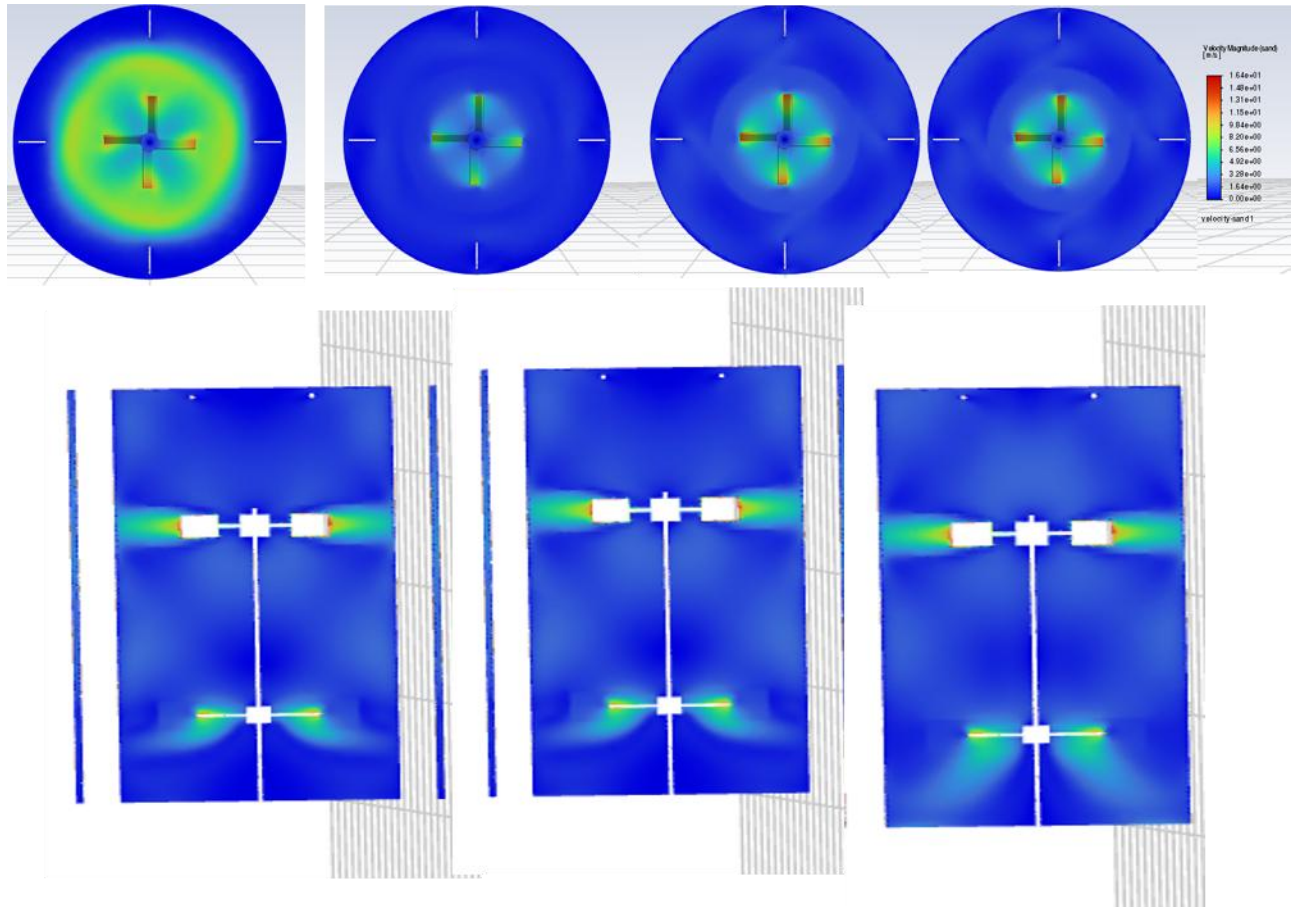


Figure 4-14: velocity evaluation

4.3.6 Fully Developed Regime (Step 200 and beyond)

In the final stage of the simulation, the system reaches a dynamically balanced state in which the mixing process is fully established. Although the flow does not become steady due to the continuous rotation of the impellers, the overall behavior of the system stabilizes in a transient sense.

The sand particles are now distributed throughout a large portion of the tank, and their motion becomes continuous and cyclic, driven by the established circulation patterns. Regions of higher concentration may still exist, but the strong segregation observed at the beginning has completely disappeared. (Figure 4.13)

This stage illustrates a realistic industrial mixing scenario, where the system operates under a dynamic equilibrium between particle suspension and settling. The impellers continuously supply

Chapter 4: Results And Discussion

energy to the system, ensuring that the particles remain in motion and that the mixing process is sustained over time. (Figure 4.14)

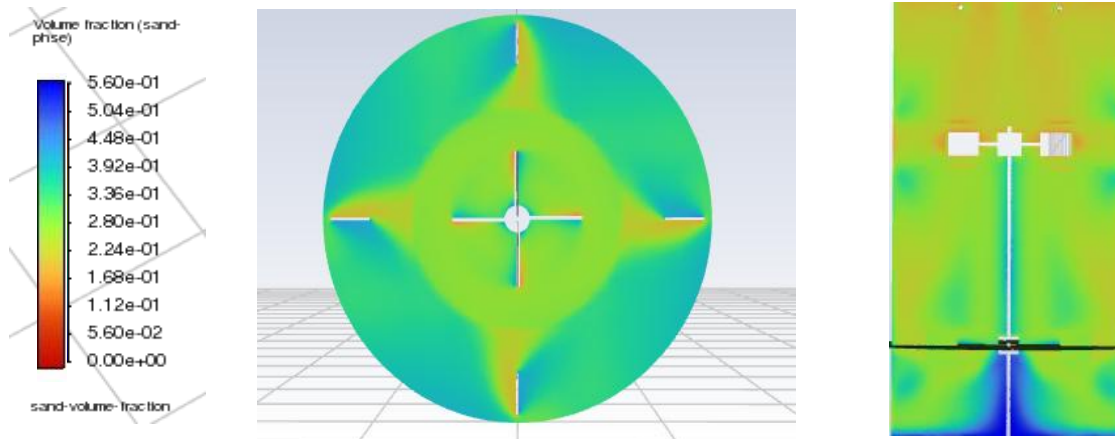


Figure 4-15 sand volume fraction on YZ view

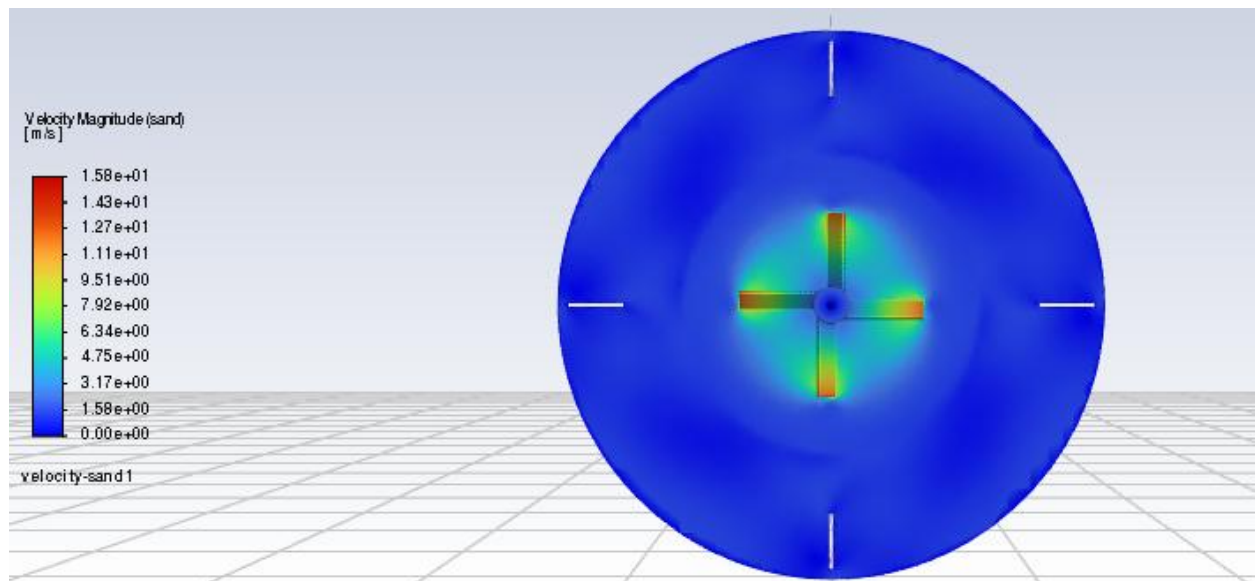


Figure 4-16: Sand Velocity

At the final stage:

- Sand is present throughout the tank
- Mixing is continuous

Chapter 4: Results And Discussion

- The system reaches a dynamic equilibrium

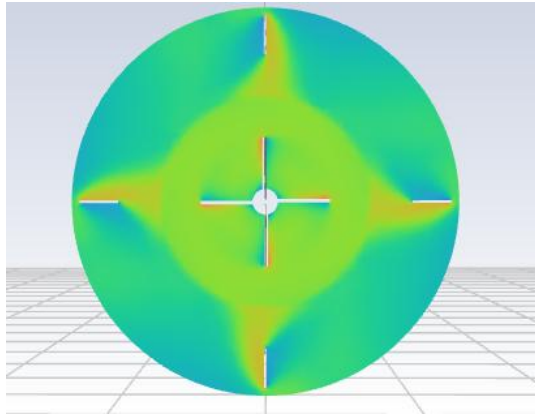


Figure 4-17: sand volume fraction on lower blade at 200 steps

Particles are constantly transported, and no complete sedimentation occurs.

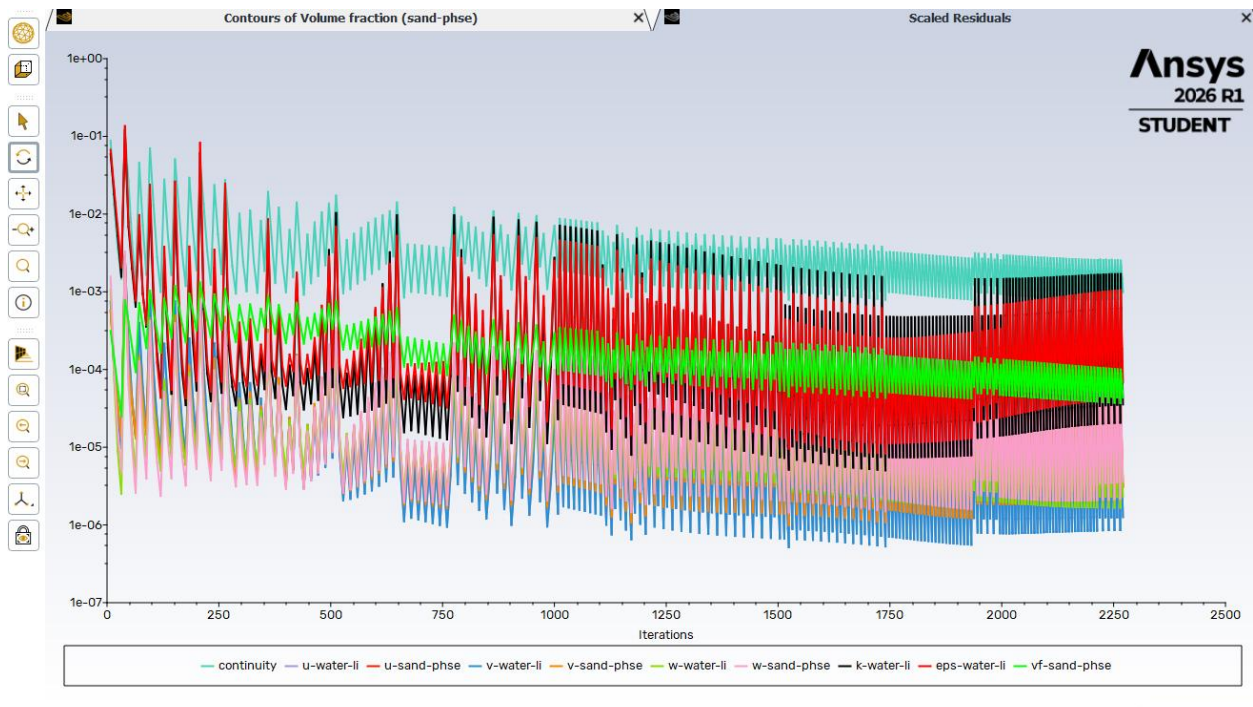


Figure 4-18: Global evolution of scaled residuals over 200-time steps showing transient convergence behavior in a multiphase mixing simulation

Chapter 4: Results And Discussion

The figure presents the global evolution of the scaled residuals over the entire duration of the simulation, covering approximately 200-time steps. This representation provides a comprehensive view of the numerical behavior of the solver and allows for a detailed assessment of convergence quality throughout the mixing process. (Figure 4.5)

At the beginning of the simulation, a very high level of residuals is observed, particularly for the continuity and momentum equations. This initial peak is expected and corresponds to the establishment of the flow field from a non-physical initial condition. During this phase, the solver rapidly adjusts the velocity, pressure, and turbulence fields, leading to a sharp decrease in residual values within the first iterations.

As the simulation progresses, the residual curves adopt a highly oscillatory pattern characterized by repetitive peaks and drops. This behavior is typical of transient simulations and is directly associated with the time-stepping procedure. At the start of each new time step, the governing equations are re-evaluated, which causes a temporary increase in residuals. As iterations proceed within the same time step, the solution converges, resulting in a decrease in residual values. This cyclic process explains the characteristic saw-tooth shape observed across all variables.

A closer examination of the graph reveals that the amplitude of these oscillations evolves over time. In the intermediate stages of the simulation, particularly between iterations 500 and 1500, the residuals exhibit larger fluctuations. This increase in amplitude reflects the intensification of the mixing process, where the interaction between the water and sand phases becomes more complex. The development of turbulence and strong recirculation zones introduces additional non-linearities into the system, making convergence slightly more demanding.

In the later stages of the simulation, the residual curves begin to stabilize, with oscillations becoming more regular and bounded within a narrower range. This behavior indicates that the flow has reached a fully developed transient regime, where the global structure of the flow no longer changes significantly from one time step to another. Despite the continuous motion induced by the impellers, the system reaches a form of dynamic equilibrium. (Figure 4.16)

It is also important to note that different variables exhibit different convergence levels. The velocity components and turbulence quantities generally reach lower residual values, often below

10^{-5} , indicating good convergence. On the other hand, the volume fraction of the sand phase shows relatively higher residuals, which is expected due to the complexity of multiphase interactions and the strong coupling between phases.

Overall, the residual levels remain within acceptable limits throughout the simulation, and no signs of divergence are observed. The consistency and stability of the residual patterns confirm that the chosen numerical setup, including time step size and solver settings, is appropriate for this type of transient multiphase flow. (Figure 4.17)

Therefore, this figure demonstrates that the simulation is both numerically stable and physically reliable, providing a solid foundation for the analysis of the mixing process presented in the following sections. (Figure 4.18)

4.4 Flow Structure and Hydrodynamic Behavior

The analysis of the contour plots reveals the progressive development of complex flow structures inside the stirred tank, which play a fundamental role in the mixing process. As the impellers rotate, they generate regions of high velocity in their immediate vicinity, where strong shear forces and turbulence are produced. These regions act as the primary source of energy input into the system.

As a result of this energy transfer, large-scale circulation loops begin to form within the tank. The fluid is driven upward in the vicinity of the impellers and then redirected downward along the tank walls, creating a continuous recirculation pattern. This organized flow structure significantly enhances the transport of momentum and contributes to the redistribution of sand particles throughout the domain.

At the same time, smaller turbulent eddies are generated, particularly near the blades, where velocity gradients are the highest. These local turbulent structures are essential for breaking the stratification of the phases and promoting particle suspension. The combined effect of large-scale circulation and small-scale turbulence leads to an increasingly efficient mixing process.

4.5 Evolution of Sand Distribution (Quantified Interpretation)

At the beginning of the simulation, the sand is completely located at the bottom of the tank due to gravity, forming a dense layer. The upper part of the tank contains only water.

As the impellers start rotating, the fluid begins to move and affects the sand particles. First, only a small portion of sand near the blades starts to move. Then, as the flow becomes stronger, more particles are lifted from the bottom.

Between step 40 and 100, the sand starts to spread inside the tank, and we can clearly see that mixing is happening. Some particles move upward, while others still fall down.

The temporal evolution of sand distribution illustrates the progressive transition from sedimentation to suspension. Initially, the volume fraction of sand α_s is close to unity at the bottom region and nearly zero in the upper zones:

$$\alpha_s(z) = \begin{cases} \approx 0.6 - 1.0 & \text{bottom region} \\ \approx 0 & \text{upper region} \end{cases} \quad (4.1)$$

In advanced stages, the distribution of α_s becomes more uniform, typically ranging between 10^{-2} and 10^{-1} across large regions of the tank. This indicates that the particles are no longer confined to the bottom and are actively participating in the flow.

At later steps, the sand becomes more distributed in the tank. It is no longer only at the bottom, but present in different regions. This means the mixing process is working correctly.

The Pressure:

–The pressure contours in the YZ plane show a clear pressure gradient inside the stirred tank. Higher pressure values are observed near the bottom of the tank due to gravity and particle accumulation, while lower pressure regions appear near the impeller blades because of fluid

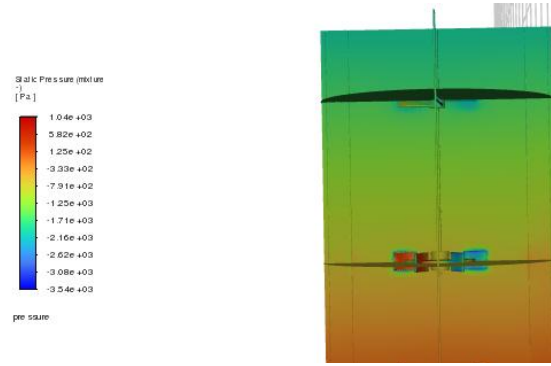


Figure 4-19: static pressure contours showing pressure gradients generated by impeller rotation during the mixing process acceleration caused by rotation. (Figure 4.19)

These pressure differences generate fluid circulation inside the tank and contribute to the transport and suspension of sand particles. The strongest pressure variations are concentrated around the impellers, confirming that they are the main source of flow motion and mixing energy.

Overall, the pressure field plays an important role in maintaining circulation and improving the mixing process inside the tank.

4.6 Interaction Between Gravity and Turbulence

4.6.1 Turbulent Kinetic Energy Distribution

The contour plots of turbulent kinetic energy (k) in the YZ plane provide important information about the distribution of turbulence inside the stirred tank.

The results show that the highest values of turbulent kinetic energy are concentrated near the impeller blades. This is expected because the impellers are the main source of energy in the system. The rotation of the blades generates strong velocity gradients and shear forces, which produce intense turbulence in these regions.

Chapter 4: Results And Discussion

In contrast, lower values of k are observed near the tank walls and in the lower regions far from the impellers. In these areas, the turbulence intensity decreases significantly, allowing gravitational effects to become more dominant.

The comparison between the turbulent kinetic energy contours and the sand distribution contours shows a strong correlation between turbulence intensity and particle suspension. Regions with high k values correspond to areas where sand particles are more dispersed and suspended, while regions with low turbulence intensity correspond to areas where particles tend to settle.

This behavior confirms that turbulence plays a major role in overcoming gravity and enhancing the mixing process inside the tank.

4.6.2 Interaction Between Gravity and Turbulence

The movement of sand particles depends on two main forces:

- Gravity $\rightarrow$ pulls particles down
- Flow/turbulence $\rightarrow$ pushes particles up

At the beginning, gravity is stronger, so sand stays at the bottom. As time increases, the impellers create stronger turbulence, which starts lifting the particles. When the flow becomes strong enough, it can overcome gravity and keep the particles moving.

The behavior of sand particles is governed by the balance between gravitational forces and hydrodynamic forces. The settling velocity of particles can be estimated using Stokes' law (for small particles):

$$V_s = \frac{(\rho_s - \rho_f)gd^2}{18\mu} \quad (4.2)$$

where:

- ρ_s : density of sand
- ρ_f : density of water
- d : particle diameter
- g : Acceleration due to gravity (9.84m/s²).

Chapter 4: Results And Discussion

- μ : Dynamic viscosity of the water

This velocity represents the natural tendency of particles to settle.

On the other hand, the turbulent velocity fluctuations generated by the impellers can be approximated as:

$$u' \sim \sqrt{k}$$

where k is the turbulent kinetic energy.

When:

$$u' > V_s$$

particles are lifted and remain in suspension. Conversely, when gravitational effects dominate, particles settle.

4.7 Relation Between Residuals and Mixing

The residual graph helps us understand how the simulation behaves numerically.

At the beginning, residuals are very high because the flow is not yet developed. Then they decrease quickly, showing that the solver is finding a solution.

Later, the residuals show a zig-zag pattern. This is normal because the simulation is transient. Each peak represents a new time step, and each drop shows convergence.

Between steps 40 and 100, the oscillations become larger. This means the flow is becoming more complex, which matches what we see physically: the sand starts moving and mixing increases.

So, the graph confirms what we see in the contour images.

Residuals represent the imbalance of the governing equations and provide a measure of how well the numerical solution satisfies the physical laws. The increase in residual oscillations during the

Chapter 4: Results And Discussion

intermediate stage corresponds to the development of complex flow structures and particle interactions, confirming that the numerical behavior is directly linked to the physical mixing process.

The residuals R can be interpreted as a measure of the imbalance in the governing equations:

$$R = \sum |\text{imbalance of governing equations}|$$

The increase in residual amplitude during intermediate stages is directly linked to:

- Stronger turbulence
- Increased phase interaction
- Higher non-linearity in governing equations

Despite these fluctuations, the residuals remain within acceptable ranges, typically between 10^{-3} and 10^{-6} , confirming numerical stability.

4.8 General Discussion

The results demonstrate that the efficiency of the mixing process depends primarily on the ratio between turbulent energy input and gravitational settling forces. This can be qualitatively expressed as:

$$\text{Mixing Efficiency} \propto \frac{\text{Turbulent Energy}}{\text{Gravitational Potential Energy}}$$

The use of the Eulerian multiphase model allows for accurate representation of phase interaction, particularly in regions of high particle concentration. Meanwhile, the MRF approach provides a computationally efficient method for simulating impeller rotation without excessive computational cost.

Chapter 4: Results And Discussion

It is also evident that the initial distribution of sand plays a critical role in the evolution of the system. A realistic initialization ensures that the simulation captures the correct physical mechanisms from the beginning.

Furthermore, the combination of global and local visualization techniques enables a comprehensive understanding of the mixing process, revealing both large-scale circulation patterns and small-scale turbulence effects.

4.9 Conclusion

The numerical simulation conducted in this study provides a detailed and physically consistent representation of solid–liquid mixing in a stirred tank.

The results demonstrate that the system evolves from a gravity-dominated regime, characterized by complete sedimentation, to a turbulence-dominated regime, where particles are effectively suspended and redistributed.

The residual analysis confirms that the simulation is numerically stable, while the physical observations validate the accuracy of the chosen modeling approach.

The study highlights the importance of impeller-induced turbulence in overcoming particle settling and achieving efficient mixing. The balance between hydrodynamic forces and gravitational effects ultimately determines the distribution of particles within the tank.

Overall, the combination of advanced numerical modeling and detailed analysis provides valuable insight into the mechanisms governing multiphase mixing processes and demonstrates the capability of CFD tools to accurately capture complex industrial flows.

Conclusion

Conclusion

The present work focused on the numerical investigation of solid–liquid mixing inside a mechanically stirred tank using Computational Fluid Dynamics (CFD). The study was motivated by the importance of maintaining a homogeneous drilling fluid during surface preparation, where the sedimentation of solid particles can significantly affect drilling efficiency and operational safety.

The first part of this dissertation introduced the fundamental concepts of rotary drilling operations, drilling equipment, and drilling fluids, highlighting the essential role of the circulation system and the importance of proper surface mixing. Theoretical aspects related to drilling fluid properties and the mechanisms governing particle suspension were also discussed to establish the scientific basis of the study.

A three-dimensional numerical model was then developed in ANSYS Fluent to simulate the mixing process of water and sand inside a stirred tank. The Eulerian multiphase approach was adopted to represent the interaction between the continuous liquid phase and the granular solid phase, while the Standard k – ϵ turbulence model was used to predict the turbulent flow generated by the rotating impellers. The numerical methodology included geometry creation, mesh generation, definition of material properties, boundary conditions, initialization, and transient simulation.

The numerical results provided a detailed understanding of the hydrodynamic behavior of the system. The analysis of velocity contours demonstrated that the impellers generated strong circulation loops responsible for transporting particles throughout the tank. Pressure contours revealed the pressure gradients that drive fluid motion, while the turbulent kinetic energy distribution confirmed the development of intense turbulence in the vicinity of the impellers. The evolution of the sand volume fraction clearly showed the progressive transition from an initially settled particle bed to a more homogeneous suspension, illustrating the balance between gravitational settling and turbulent mixing.

Conclusion

Overall, the results demonstrate that mechanical agitation is effective in reducing sedimentation and improving the uniformity of the solid–liquid mixture. The numerical model successfully captured the main physical phenomena governing the mixing process and confirmed the capability of CFD to analyze and optimize industrial agitation systems without relying solely on costly experimental investigations.

This work contributes to a better understanding of particle suspension in drilling fluid preparation and highlights the value of numerical simulation as a decision-support tool for the design and optimization of mixing equipment in the petroleum industry.

Although the present study achieved its objectives, several aspects can be investigated to further improve the understanding and optimization of solid–liquid mixing systems:

- Investigate the influence of different impeller rotational speeds (RPM) on particle suspension, turbulence intensity, and mixing efficiency.
- Compare the performance of radial-flow and axial-flow impellers to determine the most suitable configuration for drilling fluid preparation.
- Study the effect of particle size, particle shape, and solid concentration on sedimentation behavior and suspension quality.
- Perform a mesh independence study to quantify the influence of mesh refinement on the numerical solution.

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