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Erosion Damage for Various Flow Regimes During Particle Transport in Oil Wells: CFD Study

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Abstract
Oil extraction from weak sandstone formations that fails under changing in situ stresses leads to fine migration in near wellbore regions. Companies use selective completion practices or downhole filters to control particle production in oil wells. However, fines with various size dispersions will always remain that cause erosion damage in crude oil pipelines. Particles influence oil viscosity as well as density therefore impact flow regime rather than pressure drop in various depths. In this work, we employ Fluent software to simulate particle transport with the multiphase flow in the annulus that models cutting extraction during drilling rather than pipes which simulates the production process. We further estimate damage due to erosive flow under different flow regimes via adjusting various dissimilar particle dispersion functions. Results show erosion damage is at its highest value since a thin film of liquid slurry with high particle concentration forms near the inner wall pipe in the annular flow regime. Outcomes also illustrate that at high drill pipe rotation rates, flow conflicts therefore erosion damage in the annulus increases significantly.

Keywords: Erosion Damage, Particle Transport, Multiphase Flow, Crude Oil Pipeline, Flow Regime.

Introduction
Oil exploitation with high volumetric flow rates from weak formations typically originates fines migration in near wellbore regions. Companies use selective completion practices or downhole filters to decrease particle extraction from oil wells. One effective way is to employ gravel packs which screen particles that migrate from the formation to the well. Another appropriate technique to plug fragile zones is to inject resin solutions that form stiff plastics on the well's perimeter after a while. However, fines with various size dispersions will always remain, which may cause serious erosion damage in pipeline installations prior to multiphase separators. As the oleic phase comes up in well to reach surface facilities gas to oil ratio enlarges due to frictional as well as gravitational pressure drop. While two-phase flow acceleration is often negligible, thus it does not cause a significant pressure drop in wells, especially at high liquid hold-ups. Wide pressure range in wells forms various multiphase flow regimes that express unequal particle contact momentums with pipe or casing walls, therefore, various erosion damages. One must notice that selecting appropriate pipes or an effective lift design can somewhat control liquid hold-up and flow regimes. Even in cases where we extract wet or dry gas with high water percents, lower rise velocity for liquids may cause them to gather in a downhole, preventing particles from exiting effectively from wells. One way to estimate damage due to particle transport in pipelines is to apply CFD, which uses numerical analysis to imitate multiphase flow in conduits under dynamic conditions. In this way, various investigators have written articles that discuss pipe damage due to particles at different flow regimes. Sheng et al. set an assumption on multiphase pressure drop calculations that simplifies the issue to a typical gas-liquid two-phase flow in which the liquid phase carries all particles. Formulas were rewritten, adjusting updates for liquid viscosity rather than density values concerning particle characteristics. Results on simulating three-phase flow in extra-heavy oil wells show that as pressure falls during upward flow, oil viscosity, thus its carrying capacity increases that it can impact the flow regime [1]. Bello et al. used Microsoft Visual Basic programming language to develop codes that simulate particle transport in vertical oil wells and pipeline systems. Besides, these outcomes were proven using an experimental apparatus that profits from a non-invasive high-rate couple device that coapplies imaging plus particle tracking velocimetry. Results show that the 1D numerical solution can predict in situ local rather than global particle hold-up and optimal velocity or particle flux [2].

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Manzar et al. have modeled the multiphase flow of non-Newtonian rather than Newtonian slurries in horizontal pipes using CFD computations in Fluent software. One could extract frictional erosion on the pipe's internal wall by evaluating parameters like shear stress or trituration forces. Outcomes display that when the laminar flow is dominant due to low flow rates, larger particles accumulate near the lower internal wall causing severe erosion damage. In contrast, high enough volumetric flow rates cause turbulency that disperses high-momentum coarse particles in the liquid phase [3]. Ogunsesan et al. have made an appraisal CFD inquiry on erosion damage in pipes due to fine particle transport under churn along with slug flow regimes via using Fluent software. By juxtaposing damage values in multiphase flow next to the erosion rate from single-phase particle transport, it was shown that erosion damage was greater for multiphase particle transport rather than single-phase flow. Outcomes also display that phase distribution. Therefore, the flow regime significantly influences erosion damage in multiphase gas oil particle flow [4]. Fajemidupe et al. set a transparent pipe installation to experimentally investigate minimum transport conditions for various particle diameters rather than concentrations when having a laminar flow regime. Critical particle transfer velocity increases with particle diameter and concentration at ultra-low particle concentration. By using experimental liquid hold-up together with concentration, they derived an expression firstly to define particle flow regimes as particle streak and particle dune along with suspension regimes while secondly to determine pressure gradient due to friction for all flow regimes [5]. Marrah et al. used Fluent software, a CFD simulator, to calculate erosion rates during dilute particles in water mixture flow in pipelines. After that, several sensitivity analyses were also done to investigate the influence of particle size and liquid phase average velocity on erosion rate. It was shown that the usual turbulence approaches, namely k-epsilon that remarks regions far from the wall together with k-omega that magnifies near wall regions give approximately similar results when a single liquid phase carries all particles [6]. Mouketou et al. modeled particles in oil-water mixture transport in pipes using CFD commercial Fluent software, adjusting k-epsilon as turbulence approximation. Several sensitivity analyses were then done on liquid phase velocity rather than pressure dispersion to trace particle movement paths further to approximate the erosion rate. Consequences show that in contrast to particle transport in gas oil flow here, particles disperse in the whole oil-water phase; therefore, as viscosity increases, particles can less freely slip in the mixture to reach the wall; thus, erosion rate slightly decreases [7]. Liu et al. have driven correlations to estimate liquid film thickness and entrainment friction to study erosion rate in pipes under an annular flow regime. Various numerical simulations were also done to investigate the impact of factors such as liquid dynamic viscosity, pipe diameter, superficial velocities, and particle sizes on erosion damage. Comparing outcomes with experimental data showed that numerical calculations can nicely predict erosion damage due to pipeline particle transfer under high gas-to-liquid ratios [8]. Ngo et al. used multiphase computational fluid dynamics to investigate erosion damage in pipes that carry microscale particles at various gas-water flow regimes. It was shown that the erosion effect due to microscale particles strongly depends on flow patterns in pipes which in turn depends on superficial velocities for each phase. It was also shown that outcomes on erosion damage compliance forecasts come from Tulsa's multiphase erosion model [9]. Cuamatzi et al. modeled particle transport via wet gas flow in pipelines under a mist flow regime using CFD commercial Ansys Fluent software. Using the k-epsilon turbulence model, various sensitivity analyses that concern factors affecting erosion processes, such as particle size, pipe diameter, and particle concentration, were then done. Results illustrate that CFD is a practical approach in upscaling pilot size consequences to industrial scale usages [10]. Kamil et al. wrote codes in Visual Basic programming language to simulate particle transport with gas-liquid mixture flow in pipes. By referring to various erosion models, several sensitivity analyses were done on three main parameter categories: particle diameter, target material, and carrier phase characteristics. Consequences show that pipe material plus superficial phase velocities are dominant parameters affecting pipeline erosion rate [11]. Al Haidari et al. used CFD calculations via Fluent software to investigate erosion damage due to microscale corrosion products transport in dry gas pipelines for a real-case sales gas plant in Saudi Aramco. Outcomes illustrate that erosion rate increases with an increase in pressure drop in the pipeline system due to enlargement in particle diameters while also increasing sale gas velocity in pipes. Therefore, the proposal is to operate a sales gas system that carries particles under a mist regime at the lowest possible velocity while minimizing pressure drop in the piping system by reducing changes in the flow direction [12]. Sinha et al. have reviewed research on parameters such as flow properties, particle characteristics, and pipeline wall material that affects the wear rate on the internal wall whenever particle transport is in multiphase flow. It was shown that all models available in the literature incorporate a few factors which affect the process leaving other parameters aside. It was said that the main reason for this is data lack at the microscopic level rather than a change in wear mechanism under various operating conditions [13]. Kesana et al. did an experimental study to measure erosion damage in a horizontal pipe under a slug along with annular flow regimes. It was shown that the highest metal losses occur at these flow regimes that are dominant for wider industrial circumstances. Other experimental outcomes illustrate that larger particles cause more serious damage than smaller ones, while the annular flow regime is more erosive than the slug flow regime. Results also show that since terminal velocity for particle movement in sticky liquids has lower restriction values thus, highly viscous mixtures reduce average particle movement rates, decreasing erosion damage in pipes [14]. Granberg et al. modeled particle transport with dry gas in pipelines using CFD determinations in Fluent software at single-phase flow conditions. It was shown that various experimental correlations fail to attain accurate erosion damage rates at extreme flow velocities or particle sizes. Another statement was since Eulerian approaches neglect factors such as particle impingement angle or impact phenomena. The outlook is poor for accurate wear predictions in this framework [15]. Parsi et al. have done CFD calculations by applying Fluent software to simulate erosive particle transport under an annular multiphase flow regime. Several sensitivity analyses were then done on liquid rather than gas velocities to investigate erosion rates in pipes with tight changes in the multiphase flow direction. Consequences that agreed with previously done experimental results illustrate that CFD can predict maximum erosion rates under churn flow conditions with acceptable deviation from experimental data [16]. Mazumder et al. experimentally studied erosion in particle gas-liquid multiphase flow in pipes at horizontal rather than vertical sections. With varying superficial phase velocities, it was shown that since particle dispersions are not similar for the horizontal section compared to the vertical section, erosion damage rates in these two pipe sections also differ. They developed a mechanistic model to predict erosion damage in annular flow considering particle dispersion rather than the film's velocity and gas core region [17]. McLaury et al. set experiments to investigate how that pipe orientation affects particle distribution and further erosion damage in annular multiphase flow in pipes. It was shown that since fewer particles are striking in horizontal flow, the wall erosion damage is significantly greater in vertical rather than horizontal pipes. They also developed their semi-mechanistic model for erosion in pipes which accounts for variation in particle impact velocities in vertical rather than other slant orientations [18]. Zahedi et al. used Ansys Fluent software to perform CFD calculations to simulate multiphase air-water particle flow in pipelines under an annular flow regime at low liquid loading conditions. It was shown that multiphase flow quality, therefore liquid thickness, significantly affects erosion damage rate, especially in parts that flow direction changes rapidly. It was also shown that various parameters such as particle impact velocities, particle impact angle, and particle impact number dispersion in ductile could affect pipeline erosion damage.

ompared to other works in the literature, the novelty of this investigation is that firstly we study erosion damage due to particle transport in annular space rather than circular ductile at different flow patterns. Furthermore, we investigate various revolutions per minute for drill pipes to appraise damage due to cutting transport in well drilling operations. In addition, we also explore to what extent deviation from vertical direction can influence particle distribution in pipelines for each flow regime, affecting the frequency of particle contact with the pipeline wall. To do this, we employ CFD analysis by applying Fluent software that uses numerical simulation to solve multiphase flow equations in lattice networks made in Gambit software. However, one must notice that our calculations are not accurate for the mist flow regime for which the gas phase carries many fine particles.

Materials and Methods

Literature reviews several attempts to analyze multiphase flow in pipes with particle transport using computational approaches. Some investigators are concerned with physical pipeline characteristics such as diameter or dip angle. At the same time, other scientists also discuss flow regimes or wall treatment models in their computations. In this section, firstly, we explain dominant conceptual laws and formulas relevant to multiphase gas oil particle flow in pipes rather than annulus space. Afterward, we adjust various properties for particles, such as dissimilar average diameters and typical densities, to investigate how particle characteristics affect erosion damage in ductile pipes. To do this, we design three-dimensional models in Gambit software in which one pipe that expresses tubing nestles into another that exhibits casing pipe. Further, we consider that the inner pipe can rotate with different RPMs clockwise or counterclockwise inside the exterior pipe, which may have different dip angles with the vertical direction.

Since the specific gravity for calcite or quartz ores are two to three times larger than salty water, several times greater than the gas phase terminal velocity for particles that fall in lean gas is significantly larger than particles that fall in the liquid phase. Furthermore, the highly viscous oil phase makes it much harder for relatively small particles to leave the liquid phase rather than enter it. This circumstance causes almost all flow regimes from churn to mist in vertical pipes or from laminate to annular in horizontal pipes, only the liquid phase to transport all particles individually. In vertical ductile, since particles fall in the gaseous phase due to density difference except for annular regime conditions dominate

that particles pass through the viscous liquid phase, after which it is no more possible for them to re-enter the discontinuous gas phase. Even in the annular mist flow regime, if one notifies that this pattern appears in the downstream pipe after the churn flow regime, it is not too spacey to consider all particles inside liquid film on walls. In the same way, in small dip angle multiphase flow pipes, terminal falling velocity for particles is significant enough to ensure that almost all medium to large diameter particles that cause serious damage arrive into the liquid phase after a short distance. It is noticeable that the laminar regime turns turbulent at high flow rates, making small diameter particles float in the gas phase for longer distances in the pipeline. Thus, one must apply such an assumption that only liquid carries all particles more cautiously for wavy and annular mist flow regimes. Furthermore, under an annular mist flow regime, particles in a small dip angle or horizontal pipes will accumulate downer in the pipe near the lowermost wall section, causing more severe damage there. In situations where float particles are present in a liquid mixture since the specific gravity for particles we take into account is larger than the liquid phase, which is here oil or rarely water, we must also update average liquid phase density concerning particle density as size dispersion functions. The terminal velocity for spherical particles is dependent on density difference relative to fluid viscosity, which in turn depends on particle diameters. Hence different terminal velocities for various size particles do not affect calculating average mixture density since no particle accumulation occurs at steady state conditions. To determine mixture density, we first cluster continuous particle diameter dispersion curves into several smaller quantiles which exhibit even particles with set relative occurrence frequencies. Then we compute cumulative volumes rather than masses for all quantiles concerning average particle diameters and densities. Finally, we outline the specific gravity for a particle in the liquid mixture by applying an update to liquid density. In addition, float particles also affect particles in liquid mixture viscosity dependent on particle concentration and average particle

diameter. Moderate to small particles more strongly impact fluid viscosity than larger ones, perhaps due to a larger surface area per unit particle mass. To calculate liquid mixture viscosity once more, we employ quantiles from clustering continuous particle size dispersion curves to apply viscosity correction for each quantile separately. We first calculate if the flow is laminar or turbulent for any pressure drop or flow regime computation. After that, if the laminar condition is dominant, we apply the k-omega approach to represent various phase characteristics. Else when the turbulent flow is prevalent, we employ the k-epsilon approach.
After that, to simulate particle transport with the two-phase gas-liquid flow in pipes or annular spaces, we use the DPM option in Fluent software, which considers particles as a discrete phase in liquid. Finally, to define particles with various diameters to an applicable extent, we employ the normal Laplace-Gauss dispersion formula that relies on two independent parameters which determine the function's shape.

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \quad (1)$$

Using this formula, we define four different dispersion functions shown in Figures 1 to 2. The blue color diagram expresses relatively narrow particle volume dispersion, mainly from two to four millimeters in diameter. Conversely, the yellow color diagram exhibits particle volume dispersion with a similar mass flow rate, except that particle diameters, have a wider range from zero to six millimeters.

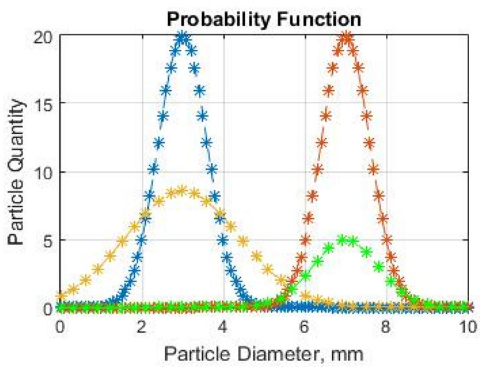

Fig. 1 Particle Diameter Dispersion Functions.

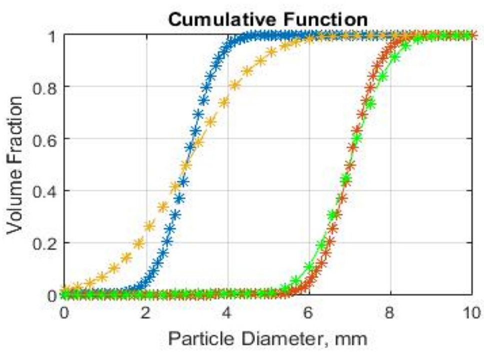

Fig. 2 Cumulative Particle Volume Dispersion.

The green color diagram illustrates the dispersion function from six to eight millimeters in diameter with the same mass flow rate as the yellow function. Finally, the red color graph also has a narrow shape with its particular mass flow rate three times larger than others. Cumulative functions which display integral area under distribution curves are also shown. Such diagrams illustrate particle size dispersion limits, whereas they exclude volumetric or mass flow rates.
The main reason for defining different types of particle diameter dispersion functions is that single-size spherical particle cannot truly show a real state when we have particle transport in production wells or cutting transport in the drilling operation. Furthermore, finer particles impact viscosity with their large surface area. In contrast, larger ones mainly affect density for liquid carrier mixtures applying different dispersion functions can act like a sensitivity analysis in investigating these influences.
One must consider pipe material characteristics rather than carrier flow properties to simulate erosion damage due to particle transport in pipes. We simplify this issue by applying a particle tracking option in Fluent CFD software that can compute contact frequencies on each wall open for particles to attack. Hence there is an issue that says large particles cause more severe damage, whereas small ones are often inherent to an iron or stainless steel pipe. We consider particle volumes by calculating the momentum flow rate to solve this. Using such an approach, we juxtapose different situations to compare erosion damage under various flow regimes without considering all details.
To compute flow regime in Fluent software, we use VOF modeling, which coincidentally solves conservation equations considering interfacial phenomena for all phases in the system. One must trace momentum flow rates in different regions with the solution space to draw multiphase flow regimes. Local districts with large momentum flux values express the liquid phase, whereas sectors with small fluxes exhibit the gas phase.
As crude oil comes up in the well to reach surface facilities, the pressure falls under the saturation point, causing gas to release from the oil phase gradually. By moving to downstream sections in wells or pipelines, higher pressure drop enlarges quality for two-phase flow in two ways, firstly due to oil shrinkage and free gas expansion. This effect forces us to consider flash calculation that relies on an EOS to predict how volatile components come out of crude oil to go into the gas phase concerning pressure and temperature. There are two approaches using phase equilibrium calculations: simple flash, in which one can apply Depriester k-value chart to illustrate volatilities, and more accurate flash calculation, using an EOS like PR or SRK to update fugacities after that k-values to solve the problem in a trial error process.

$$y_i=k_i x_i \quad z_i=Vy_i+Lx_i \quad (2)$$

$$x_i=\frac{z_i}{V(k_i\text{-}1)+1} \quad y_i=\frac{k_i z_i}{V(k_i\text{-}1)+1} \quad (3)$$

$$\sum y_i=1 \quad \sum x_i=1 \quad (4)$$

For lightweight components, k-values are much larger than unity, whereas heavier constituents have small k-values. Each step algorithm appraises mixture quality and k-values from an EOS to achieve a condition that satisfies compositions in each phase. Since Fluent itself cannot perform phase equilibrium calculations, we use the UDF option to import flash calculation outcomes as tables containing various phase compositions and flow quality for various pressures at a set temperature value. Tabular data comes from a PVTsim simulator that applies a compositional approach and an EOS to forecast hydrocarbon mixture properties in two-phase regions.

To perform CFD analyses in Fluent software, we define two main scenarios: two-phase gas oil exploration from annular space and inner pipe which carries spherical particles of different diameters in line with another scenario that contemplates cutting transport via single-phase liquid drilling mud in annular space under drill pipe rotation. Since oil shrinkages as pressure fall whenever moving downstream in wells or pipelines, its viscosity, therefore, carrying capacity increases. To compute oil viscosity, we apply flash calculation after that property estimation using PVTsim software. Wherever the carrier phase is drilling mud, there is only one non-Newtonian liquid phase for which the viscoplastic approach explains its viscosity, which depends on the rate. Table 1 expresses carrier phase characteristics.

Table 1. Physical Characteristics for Carrier Flow

Carrier Flow	API°	Temp
Volatile Oil	45.0	F° 140
Drilling Mud	-65.0	F° 110
Composition	C1	C7+
Volatile Oil	% 65	% 11
Visco Function		
Drilling Mud	cp 35	10

To perform numerical determinations in Fluent software, one must create a mesh network using Gambit software. First, we set various designations from two-dimensional cross-section models to more realistic three-dimensional geometries to simulate particle transport in multiphase flow. For example, a triangular mesh network fits curvatures nicely, while rectangular shapes can set to triangular or quadrilateral mesh with high precision. It is also noticeable that for an efficient simulation, we put finer mesh for near-wall regions while the coarser mesh is far from walls. Figure 3 shows one typical process in Gambit.

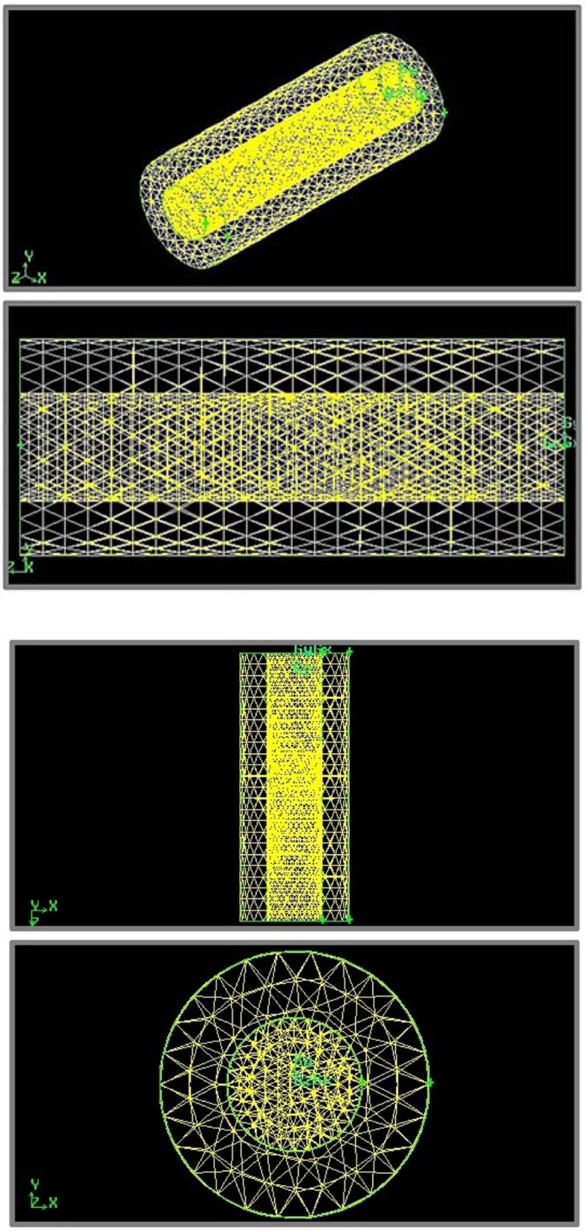

Fig. 3 Two Pipes that Nestles each other Tubing Casing Model.

Results and Discussion

In this section, we first explain to what extent particles can change particle in liquid mixture characteristics like specific gravity or viscosity for two main carrier phases: drilling fluid and volatile oil. Afterward, we display various regimes for multiphase flow in vertical rather than horizontal circular cross-section ductile from CFD calculations that concern conservation equations and interfacial phenomena. Furthermore, we estimate erosion damage due to particle transport in pipes that carry volatile oil and models for which drilling fluid carries cuttings in annular space to surface pits. Finally, we display to what extent flow regimes can affect erosion damage rate in various dip angle pipes and annuluses. Since quartz or dolomite densities are higher than volatile oil as their carrier liquid phase, an increase in particles increases the specific gravity for the liquid mixture. This increase relies on average particle diameter and is not dependent on particle size dispersion function. Since specific gravities for quartz or dolomite minerals are set values, liquid mixture density only relies on the total particle mass flow rate.

As volatile oil shrinkages when moving to low-pressure downstream wells or pipelines, its density increases when more volatile components exit the liquid phase. This increase linearly affects the specific gravity of oil mixture particles shown in Figure 4.

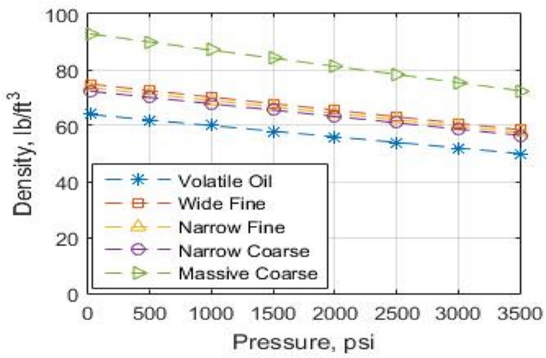

Fig. 4 Densities for Particles in Oil Mixtures.

Density values for the particle in oil mixtures with three dispersion functions, namely narrow fine wide fine, and narrow coarse, are almost the same since their total particle mass flow rate is similar. Conversely, specific gravities for massive coarse dispersion are three times larger than others due to the higher total particle mass flow rate.

In front of mixture density, which is only provisional to average particle diameters, viscosity for a particle in a liquid mixture relies not only on average volumes yet on size dispersion curves. Liquid mixture viscosity increases with a reduction in pressure, nonlinearly with increasing order. The main reason is that the function that relates liquid mixture viscosity to particle concentration is not linear. As shown in Figure 5, liquid mixture viscosity for fine particles is larger than for coarse particles due to their much greater surface area, which applies much higher drag forces during particle transport. It is noticeable that wider-in-range fine particles exhibit higher mixture viscosities since smaller particles are present in the mixture under such circumstances.

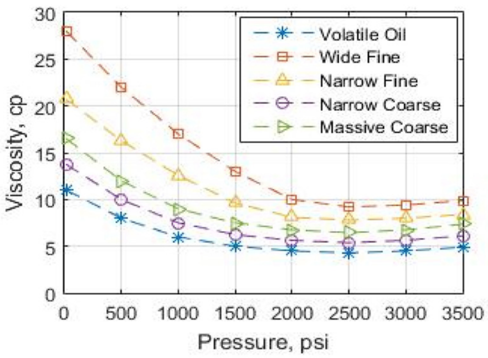

Figure 5. Viscosities for Particle in Oil Mixtures.

Similar influences appear when working with drilling fluid as a carrier phase for small cuttings. Here, drilling mud viscosity similarly relies on average particle diameter rather than mineral density, which is not conditional to particle diameter dispersion functions. But since typical drilling muds are aqueous solutions, they do not evaporates as pressure falls in annular space to reach surface pits. Therefore one can express set values for drilling mud viscosities and densities concerning pressure values when carrying various particles, as shown in Table 2.

Table 2 Viscosity Appraisals for Particle in Drilling .Fluid Mixtures.

Particles	Sp. Gr	Viscosity
Pure Drilling Fluid	2.69	cp 35.0
Narrow Class Fine	2.79	cp 44.4
Wide Class Fine	2.77	cp 48.3
Narrow Class Coarse	2.78	cp 38.7
Massive Class Coarse	2.93	cp 42.6

Since total mass flow for particle transport with dispersion schemes from narrow class fine to wide class fine further to narrow class coarse are equal, we see almost the same specific gravities for all cases, which is slightly larger than pure drilling fluid with no cutting *particles*. As a liquid mixture contains finer in size particles, its viscosity deviates more from pure drilling mud without particles, whereas coarse particles can only increase its relative weight. Both increases in density or viscosity will affect pressure drop, yet erosion damage in the annulus.

To determine erosion damage due to particle transport in pipes or annular space, the first step is to specify conditions for which various flow regimes form. Each flow pattern exhibits liquid quantity; particle contacts the pipe's inner or outer wall. As shown, particles affect liquid mixture viscosity and density, influencing regime change limits and pressure drops. To compute flow regime, Fluent software solves equations for phase interface forces together with momentum as well as mass conservation equations to achieve phase dispersion in each node with the mesh network made in Gambit.

In zero-angle pipes, whenever superficial flow velocities are, a low laminate regime is dominant in which all particles accumulate in the lower pipe section that contains the liquid phase. Since flow rates increase, the liquid surface starts to sway with uniform or nonuniform dispersion that exhibits a wavy flow regime. In such circumstances, larger conflicts in liquid phase streamlines intercept small particles from settling on the pipe's lowermost wall. At extremely high multiphase flow rates, the annular flow regime is dominant in which a thin liquid film carrying all erosive particles covers the inner wall.

One must notice that gravity force affects this thin film to make it off-center concerning the pipe's central axis. Further, in this study, we illustrate to what extent such an effect can influence damage due to particle transport in near horizontal pipes. Various flow regimes for zero-angle pipelines are shown in Figure 6.

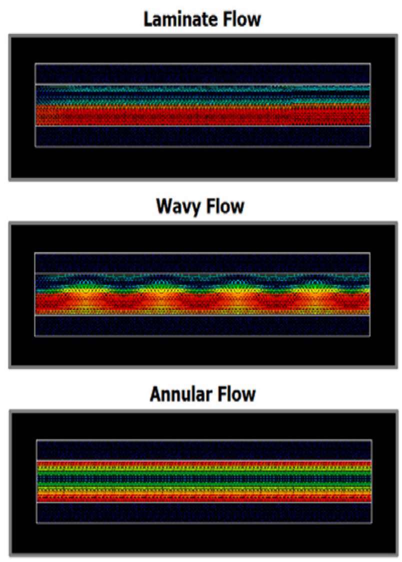

Fig. 6 Flow Patterns in Horizontal Pipe Model.

Since superficial velocities for multiphase flow increase in vertical wells, gas globules merge, forming bigger gas pockets in slug flow. During this regime, periodical high to low thenceforth, and vice versa, low to high particle concentration waves pass across each pipe section perpendicular to the flow direction. As superficial multiphase velocities increase even to higher values, this periodical flow turns into irregular unsteady fluctuations in liquid quality. In such circumstances, one cannot truly track particles to determine erosion damage. Under situations with higher flow rates, an annular flow regime appears for which a symmetric thin film that carries all small to large particles will cover the pipe's inner wall. Like small dip angle pipelines in vertical pipes, this flow pattern is the most erosive regime for two main reasons. Firstly high particle concentrations in a thin liquid film near the inner wall cause several particle contacts. Secondly, high true liquid velocities can hardly damage the internal pipe's wall. Various flow regimes for vertical pipelines are shown in Figure 7.

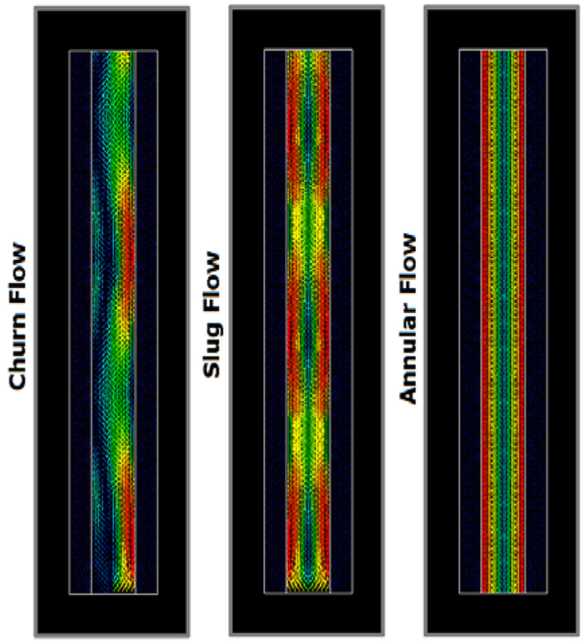

Fig. 7 Flow patterns in vertical tubing model.

According to the results shown in Table 3, particle dispersion functions strongly influence flow patterns in volatile oil pipes that transport particles. In vertical pipes, as particles enlarge, liquid mixture viscosity increases, which causes the flow regime from annular to churn further to slug. Similarly, particle diameters decrease flow patterns in small-angle volatile oil pipes, varying from annular to wavy to laminate.

Table 3 Maximum momentum flow for particle contacts on the pipe wall.

Momentum(lb/min)	0°	45°	90°
Narrow Class Fine	0.06	0.06	0.05
	Wavy	Wavy	Churn
Wide Class Fine	0.05	0.04	0.03
	Laminate	Wavy	Slug
Narrow ClassCoarse	0.09	0.08	0.07
	Annular	Annular	Annular
Massive Class Coarse	0.08	0.06	0.05
	Annular	Wavy	Churn

From an erosive flow viewpoint, multiphase flows that contain larger coarse particles are more prone to erosion. In contrast, those with small particles exhibit higher viscosity, which does not allow cheap particles to attack pipe walls. Since cutting transport with drilling fluid is only a liquid mixture phase, no flow regimes exist to discuss. Erosive effects are thus dependent on particle dispersion in oleic or watery mud, according to the results shown in Table 4.

Higher rotation velocities for drill pipes cause severe particle contact with the inner pipe's wall, indicating erosion damage—two facts cause such an effect. Firstly, in this case, the hydraulic diameter for annulus is much larger than the inner pipe diameter. At the same time, the viscosity of drilling mud is much higher than volatile oil, preventing particles from freely attacking the wall.

Table 4 Maximum momentum flow for particle contacts on the casing wall.

Momentum Flow	0°	45°	90°	
Narrow Class Fine	0.0019	0.0018	0.0017	RPM = 200
Wide Class Fine	0.0014	0.0014	0.0014	
Narrow Class Coarse	0.0026	0.0024	0.0023	
Massive Class Coarse	0.0020	0.0020	0.0019	
Momentum Flow	0°	45°	90°	
Narrow Class Fine	0.0026	0.0023	0.0021	RPM = 300
Wide Class Fine	0.0022	0.0020	0.0019	
Narrow Class Coarse	0.0033	0.0030	0.0027	
Massive Class Coarse	0.0028	0.0026	0.0023	
Momentum Flow	0°	45°	90°	
Narrow Class Fine	0.0046	0.0044	0.0040	RPM = 700
Wide Class Fine	0.0042	0.0040	0.0039	
Narrow Class Coarse	0.0056	0.0049	0.0044	
Massive Class Coarse	0.0048	0.0046	0.0040	

As rotational velocity for drill pipes increases from typical to higher values, the momentum flow rate for particles attacking the surface significantly increases, increasing erosion damage. Authors argue that high RPMs for drill pipes cause laminar flow in the annulus to disturb, slowly changing from laminar to turbulent flow, leading to much stronger particle contact with the casing wall.

It is also noticeable that all our predictions or flow simulation outcomes in annular space are reliable only when drill pipes place completely centric in the hole. This is because any deviation from the center point causes an extreme impact on flow regimes rather than pressure drops or even damages due to particle transport. In such circumstances, one can predict that greater damage occurs in narrow regions rather than broader sectors, as shown in Figure 8.

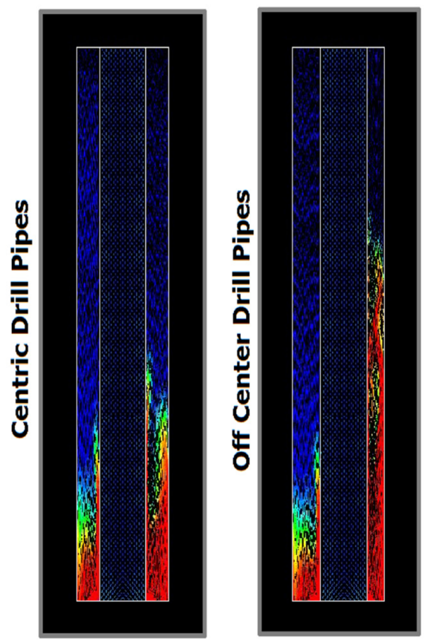

Fig. 8 Particle Movement when Drill Pipes are at Hole Center or off Center

Conclusions

Several key findings from this present article are as follows:

1- Particle diameter dispersion curves impact pressure drop rather than flow regime by applying changes to liquid phase viscosity and specific gravity. Liquid mixture carries almost all particles from small to the large volume in nearly all flow regimes.

2- Larger particles affect liquid density, while smaller particles with higher surface area strongly impact liquid viscosity. Therefore, viscosity values for a particle in volatile oil mixtures are nonlinearly varied with pressure, while density values have a linear procedure.

3- Particle size distribution functions impact multiphase flow patterns in vertical pipes as well as slant or horizontal pipes. Particles with small diameters increase liquid phase viscosity; therefore, try to prevent the regime from turning into the annular flow.

4- For two main reasons, annular flow exhibits the greatest damage due to erosive flow. Firstly, all particles accumulate in a thin film that covers the inner wall. At the same time secondly, linear flow velocities are extremely high in that thin liquid film that causes particles to attack the pipe wall repetitively.

5- At high drill pipe rotational velocities, flow conflict increases, causing momentum flow rate for particles that attack the surface; therefore, spherical particles or damage due to erosive flow increases significantly. This is while flow in the real-size annulus is typically laminar.

Conflicts of Interest

Here the main author confirms that there are no persons other than the authors on the title page who satisfy the criteria for authorship. Furthermore, the principal author affirms that we have given due consideration to protecting intellectual properties in this work, so there is no conflict of interest.

Nomenclatures

CFD: Computational Fluid Dynamics
EOS: Equation of State
UDF: User Defined Function
VOF: Volume of Fluid

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