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Performance Analysis of Coiled Tubing in Sand Cleanouts: Understanding Slip Velocity and Pressure Drop

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Abstract

Coiled tubing (CT) sand cleanout operations are an essential aspect of well intervention, particularly in reservoirs prone to sand production and accumulation. These operations aim to remove obstructions that impede fluid flow within the tubing or annulus, thereby restoring and maintaining well productivity. This study investigates the impact of fluid properties, specifically density and viscosity on slip velocity and frictional pressure loss within the CT system during cleanout processes. The results demonstrate that fluids with higher viscosities, such as diesel, require increased flow velocities to effectively suspend and transport sand particles, reducing the risk of settling. Conversely, higher fluid densities are associated with increased frictional resistance along the tubing walls, resulting in greater pressure losses. The study further examines the correlation between flow rate and frictional pressure drop, revealing that elevated flow rates lead to increased hydraulic losses, potentially affecting operational integrity. A key observation is the transition from laminar to turbulent flow regimes with rising flow rates, which significantly influences sand transport efficiency and overall system behavior. These findings highlight the importance of careful fluid selection and flow rate optimization to enhance cleanout performance. By understanding the interplay between fluid dynamics and system design, operators can improve the efficiency and reliability of CT sand cleanout operations.

Keywords: *Coiled tubing; Density; Viscosity; Flowrate; Cleanout operation.*

1. Introduction

Coiled tubing technology (CT), is widely utilized to deliver equipment and supplies during corrective work on producing wells. Coiled tubing is utilized to address three crucial requirements for downhole operations. Firstly, it provides a dynamic seal that separates the formation pressure from the surface. Secondly, it serves as a continuous channel for fluid conveyance. Lastly, it offers a technique for maneuvering this conduit into and out of a pressurized well [1]. The primary application of coiled tubing is the elimination of fill items that impede the flow through tubing or casing. These fill materials can disrupt production by obstructing the flow of oil or gas, as well as hinder the operation of downhole control equipment such as sleeves and valves. Common sources of fill include reservoir sand or fine material, proppant materials used in hydraulic fracturing operations, workover debris, and organic scale. The removal of fill is typically achieved through coiled tubing. by pumping a cleanout fluid, which can be The CT utilizes a jet nozzle at its end to propel either water or brine, effectively transporting debris back to the surface through the annulus between the CT string and the completion tubing [2]. Compared to traditional drilling and workover operations, CT equipment and procedures offer notable benefits. These advantages include quicker mobilization and rigging-up, reduced staffing requirements, a smaller environmental impact, and less time spent on pipe overseeing during pit operations. These abilities are especially useful in high-angle or deep wellbores. Coiled tubing helps operators prevent the possibility of formation damage or well control that can happen when a well is shut down by allowing continuous circulation during well intervention procedures. When compared to conventional drilling or workover techniques, these benefits can result in significant cost savings [3-4].

Sand requires clean out operations to get rid of accumulated debris from the wellbore. However, the process is not always simple. When the fluid velocity inside the hole is insufficient to move the sand particles to the surface, the particle to accumulate and settle in the hole, in addition, during cleanout operations, friction pressure loss may occur as the coiled tubing or other intervention tools encounter resistance from fluids and sand, thus this friction affects the effectiveness of the cleanout process, extending the time and resources required to finish the procedure successfully [5-6]. Additionally, an experimental investigation was conducted [7] to quantify the frictional pressure losses in horizontal and highly inclined wells, considering pipe rotation and the existence of cuttings. Numerous studies on cuttings transport were conducted using different mud systems with varying rheological and physical properties on the METU Cuttings Transport Flow Loop. Empirical correlations were developed to predict frictional pressure losses in a horizontal wellbore, considering pipe rotation and the presence of cuttings. The equations were found to be reasonably accurate when compared to actual frictional pressure loss data. It was observed that the effect of pipe rotation is more significant when the fluid is non-Newtonian. Moreover, an increase in the concentration of cuttings in the wellbore results in higher frictional pressure losses [8-9], discussed the various sand cleanout methodologies, as well as the benefits and drawbacks of each. Methods discussed include Stationary circulation hole cleaning, Wiper trip hole cleaning, Reverse circulation hole cleaning, Sand vacuuming and sand/junk bailers.

Case studies demonstrate how to choose the appropriate cleaning approach. The paper proposed a flowchart to select hole cleaning method and how to optimize the cleaning process. An experiment to investigate sand cleanout in horizontal wellbores using the study conducted [10] involved testing water and viscous polymer-based fluids with three different polymer concentrations. The findings indicate that water triggers cutting movement at lower flow rates compared to polymer solutions, while fluids with high polymer content and increased viscosity require higher flow rates to start eroding the bed. Critical velocity and wall shear stress needed to initiate bed erosion was also determined. Sand-sized cuttings ranging from 260 to 1240 microns were used in the experiment. The results show that intermediate-sized cuttings are more easily removed, whereas smaller and larger cuttings are more challenging to transport, requiring higher flow rates and pressure losses. Flow loop studies were performed [11-12] and the efficiency of cleanout for three fluids was evaluated in a 10.36 m long horizontal annular (127 mm x 60 mm) test section. Flow rates varied from 5.04 to 9.46 l/s. Unlike the previous study, this research focused on determining the reduction in bed height and the removal of solids. The findings indicated that fluids with low viscosity exhibited higher near-bed fluid velocity and turbulence, resulting in better cleanout efficiency. Increased fluid velocity and turbulence aided in lifting particles from the cuttings bed. The effects of flow rate and viscosity on cleanout efficiency were analyzed through dimensional analysis. A generalized correlation was developed through non-linear regression to scale up the experimental data. The main goal of this study is to assess the impact of various parameters. such as the size of sand particles, flow rate, and the coiled tubing diameter on slip velocity and friction pressure loss in the context of sand cleanout using coiled tubing unit.

2. Methodology

The analysis of sand cleanout performance focuses on evaluating the effects of fluid classification and coiled tubing diameter on sand slip velocity and pressure drop during flow, as presented in Tables 1 and 2. Furthermore, Table 3 summarizes the parameters employed in the assessment of friction pressure gradient and slip velocity.

Table 1. Types of fluids characterized by their density and viscosity.

Fluid Type	Density (ppg)	Viscosity (cP)
Seawater	8.526	1.0126
Diesel	7.115	2.7246
Kerosene	6.70	1.5888

Table 2. Coiled tubing Specifications.

O.D (In.)	I.D (In.)	Weight (lb./ft)
2.375	2.063	3.7
2	1.688	3.07
1.75	1.438	2.66
1.5	1.376	2.24

Table 3. The parameters used to analyze slip velocity and friction pressure gradient.

Type of fluid	CT inner diameter (inch)	Diameter of sand (inch)	Flow rates (gal/min)
Seawater, diesel, kerosene	1.376,1.438,1.688, 2.063	0.01, 0.03, 0.05, 0.08	40, 60, 80, 100, 120, 160, 180

This study utilizes the Cerberus software, a computational fluid dynamics (CFD) tool designed for wellbore analysis and intervention planning. Cerberus offers advanced capabilities such as 3D visualization, machine learning algorithms, and integrated optimization techniques. As illustrated in Figure 1, the software includes multiple modules such as Reek-Trak, Hydra, Packer, Completion Analysis (PACA), Orpheus, Velocity String, and solids Cleanout each tailored to specific aspects of downhole operations. For this analysis, the Hydra module is employed to compute sand slip velocity under various operational conditions. The software's Settling Velocity Calculator, shown in Figure 2, allows users to modify key input parameters, including pump rate, coiled tubing outer and inner diameters, and fluid type, enabling a comprehensive evaluation of cleanout efficiency.

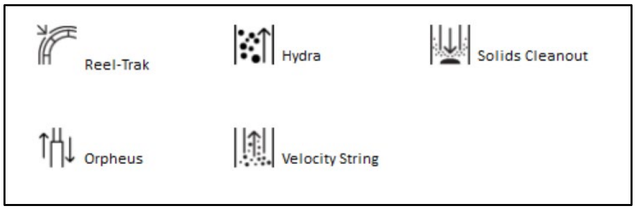
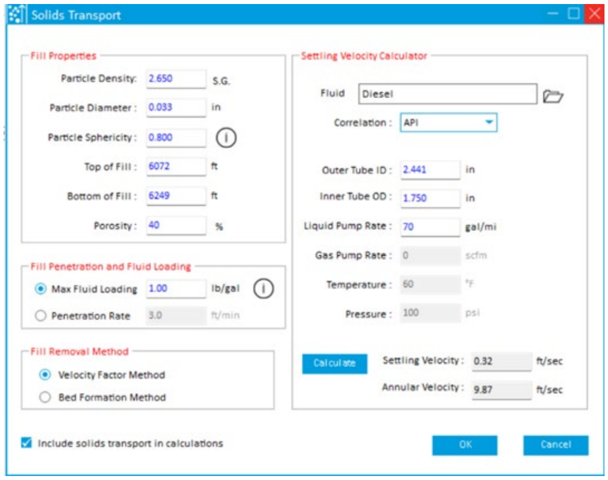


Figure 1. Configuration for Cerberus software.



Particle Density: 2.650 S.G.
Particle Diameter : 0.033 in
Particle Sphericity : 0.800
Top of Fill : 6072 ft
Bottom of Fill : 6249 ft
Porosity : 40 %

● Max Fluid Loading 1.00 lb/gal
○ Penetration Rate 3.0 ft/min

● Velocity Factor Method
○ Bed Formation Method

Fluid Diesel
Correlation : API
Outer Tube ID : 2.441 in
Inner Tube OD : 1.750 in
Liquid Pump Rate : 70 gal/mi
Gas Pump Rate : 0 scfm
Temperature : 60 °F
Pressure : 100 psi
Settling Velocity : 0.32 ft/sec
Annular Velocity : 9.87 ft/sec

☑ Include solids transport in calculations

Figure 2. The Cerberus software offers a mode for transporting solids.

A comprehensive mathematical model for estimating pressure loss in pipes is provided by the Darcy–Weisbach equation, also known as the universal equation. As shown in Equation 1, this equation calculates frictional pressure drop by incorporating both conduit and fluid properties. It is applicable across various pipe diameters and materials, making it a versatile tool for analyzing flow behavior in coiled tubing and other piping systems.

$$\Delta P = f.\frac{L}{D}.\frac{\rho V^2}{2} \tag{1}$$

In Equation 1, ΔP represents the pressure drop gradient, expressed in psi/ft. The friction factor *f* is a dimensionless parameter that depends on flow regime and pipe roughness. The pipe length *L* and the coiled tubing diameter *D* are measured in feet, while the fluid density *ρ* is given in pounds per cubic foot (lb./ft³). The fluid velocity *V*, expressed in feet per second (ft/s), is calculated using Equation 2. These parameters collectively determine the frictional pressure loss along the tubing during sand cleanout operations.

$$V = \frac{Q}{A} \tag{2}$$

In Equation 2, *Q* denotes the volumetric flow rate, measured in cubic feet per second (ft³/s), while *A* represents the cross-sectional area of the coiled tubing, measured in square feet (ft²). The dimensionless Darcy–Weisbach friction factor (*f*) quantifies the resistance encountered by the fluid as it flows through the pipe. This friction factor is determined using the Moody chart, as shown in Figure 3. Prior to using the chart, the relative roughness of the pipe must be calculated, since varied materials exhibit varying degrees of surface roughness. The relative roughness is computed using Equation 3, which relates the pipe's absolute roughness to its internal diameter. In this study, the coiled tubing is made of stainless steel, with an absolute roughness of 45.7 microns (0.000149934 feet). Once both the Reynolds number and the relative roughness have been established, the friction factor can be obtained from the Moody chart. This value is then used to determine the frictional pressure gradient in the tubing system.

$$Relative\ pipe\ roughness = \frac{\varepsilon}{D} \tag{3}$$

whereas ε is the absolute pipe roughness, ft.; D is the diameter of the coiled tubing, ft.

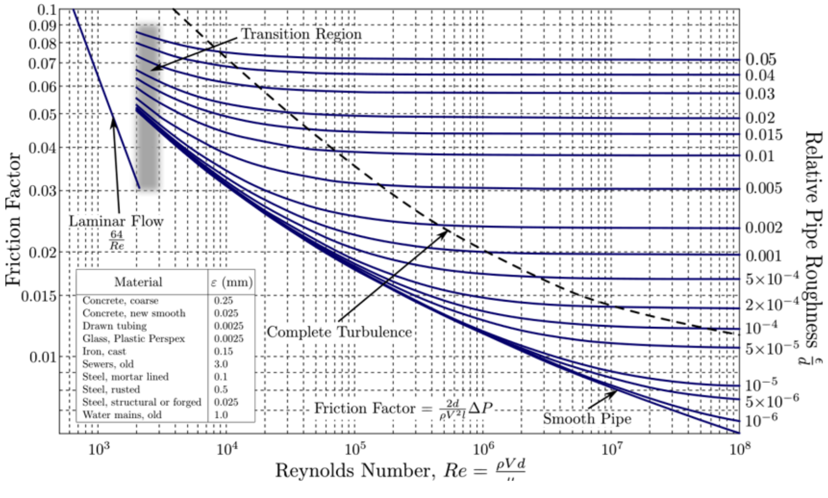


Figure 3. Moody chart.

3. Results and discussions

Figure 4 illustrates the variation of slip velocity as a function of sand particle size. The results indicate that slip velocity increases with fluid viscosity. Among the fluids analyzed, diesel having the highest viscosity requires a higher flow velocity to prevent sand particles from settling. Additionally, slip velocity increases with sand particle size due to the greater mass of larger particles, assuming constant material density. As particle size increases, the

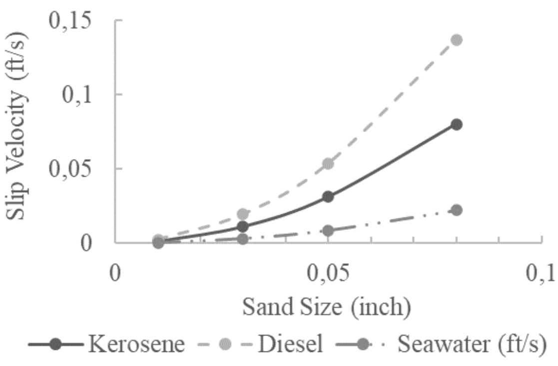
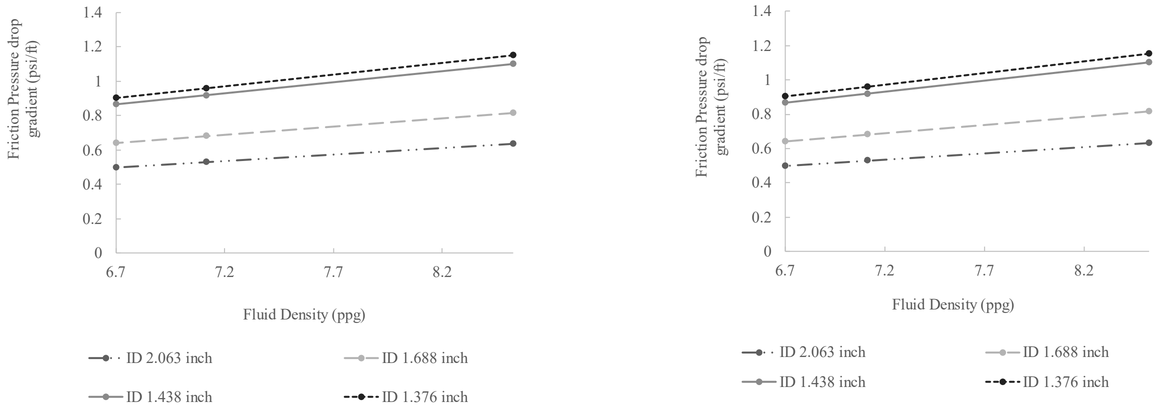


Figure 4. Slip velocity in relation to the size of sand particles.

gravitational force acting on the sand becomes more significant, enhancing the tendency for particles to settle. This highlights the importance of accounting for both fluid properties and particle size in the design of effective sand cleanout operations.

Figure 5 presents the relationship between frictional pressure drop and fluid density for various internal diameters of coiled tubing, evaluated at flow rates of 40 gal/min and 80 gal/min. The results show a clear trend: as fluid density increases, the corresponding frictional pressure drop also rises.

This behavior is attributed to the direct influence of fluid density on the mass flow rate within the coiled tubing system. For a constant volumetric flow rate, denser fluid carries more mass per unit volume, leading to a higher mass flow rate. This, in turn, increases the momentum of the flowing fluid and enhances frictional interactions with the tubing walls, thereby resulting in a higher pressure drop. These findings underscore the significance of fluid density in cleaning out hydraulic performance, particularly when selecting fluids for operations involving varying tubing diameters and flow conditions.

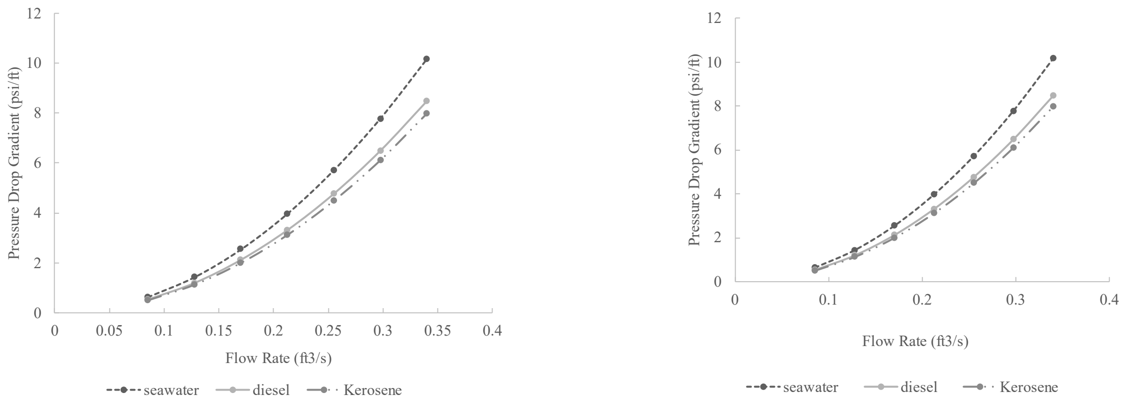


(a) Friction pressure loss against fluid density at 40 gal/min.

(b) Friction pressure drop against fluid density at 80 gal/min.

Figure 5. (a) Friction pressure loss against fluid density at 40 gal/min. (b) Friction pressure drop against fluid density at 80 gal/min.

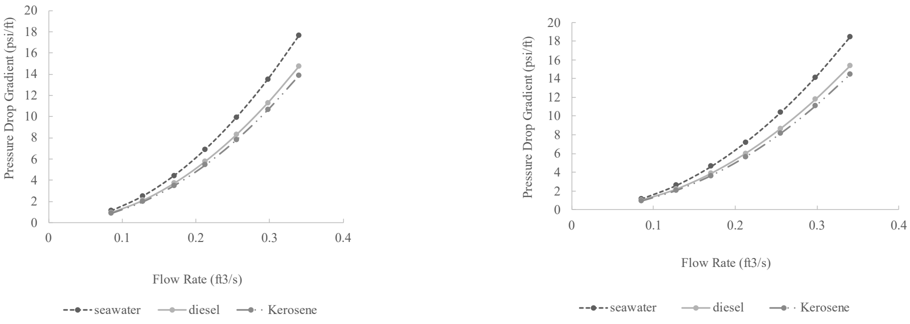
The relationship between pressure gradient and flow rate in coiled tubing with diameters of 2.063", 1.688", 1.438", and 1.376" is depicted in Figures 6 and 7. As flow rate increases, the pressure gradient decreases due to the enhanced frictional effects. This phenomenon occurs because, at higher flow rates, the fluid inside the coiled tubing moves at faster velocities, resulting in increased frictional resistance along the tubing walls. Consequently, the pressure gradient declines as the flow rate rises. Additionally, at elevated flow rates, the fluid exerts greater shear stress on sand particles within the wellbore. This increased shear stress can lead to the mobilization and suspension of sand particles in the fluid, potentially raising the friction pressure as these particles are carried along with the flow. Furthermore, at higher flow rates, the flow regime within the tubing may transition from laminar to turbulent flow. The onset of turbulence results in higher frictional losses due to the chaotic mixing of fluid layers, which exacerbates frictional pressure losses along the tubing walls.



(a) The pressure drops against flow rate - 2.063” tubing size.

(b) Pressure drops against flow rate - 1.688” tubing size.

Figure 6 The pressure gradient against versus flow rates.

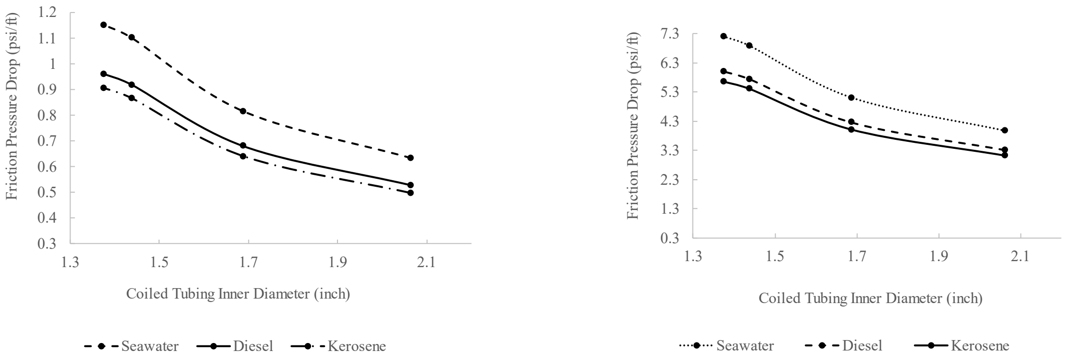


(a) pressure drop against flow rate in 1.438 tubing..

(b) Pressure drops against flow rate in 1.376” tubing.

Figure 7. Pressure drop against various flow rates.

Figure 8 illustrates the impact of varying coiled tubing diameters on frictional pressure drops for different fluid types, including diesel, water, and light oils, at flow rates of 40 gal/min and 80 gal/min. The results indicate that larger coiled tubing diameters lead to reduced frictional pressure drops due to an increased surface area for fluid contact, which reduces the frictional resistance between the fluid and the tubing walls. Conversely, smaller tubing diameters result in higher frictional resistance as the fluid has less surface area in contact with the tubing. This increased frictional resistance is particularly evident when using highly viscous fluids such as diesel, which tend to increase frictional losses compared to lower viscosity fluids like water or light oils. In addition to the effects of tubing diameter, the flow regime can transition from laminar to turbulent as the tubing diameter decreases, particularly at higher flow rates. The transition to turbulent flow, especially at flow rates of 80 gal/min, is characterized by chaotic fluid movement and mixing of fluid layers, leading to a significant increase in frictional losses and pressure drop. This phenomenon is more pronounced with higher-viscosity fluids, as the increased fluid viscosity exacerbates the effects of turbulence, further amplifying the frictional pressure losses. These findings underscore the importance of optimizing tubing diameter and flow rate in conjunction with fluid type to minimize frictional losses and improve the efficiency of sand cleanout operations.



(a) Friction pressure drops against coiled tubing diameter at 40 gal/min using different fluid types.

(b) Friction pressure drops against coiled tubing diameter at 100 gal/min using different fluid types.

Figure 8. Friction pressure drops against coiled tubing diameter using several types of fluids.

4. Conclusions

The use of coiled tubing in sand cleanout operations offers a comprehensive solution for maintaining well productivity in sand-prone reservoirs. This study highlights key factors that influence the efficiency and effectiveness of sand cleanout procedures by examining fluid properties, flow rates, and tubing characteristics. Fluid parameters, such as viscosity and density, directly affect slip velocity and frictional pressure drop within the coiled tubing system. Higher viscosity fluids, such as diesel, necessitate higher velocities to prevent sand from settling. However, increasing fluid density results in greater frictional resistance along the tubing walls, underscoring the need for careful fluid selection to optimize cleanout performance. Additionally, an analysis of flow rates reveals a significant relationship between flow velocity and frictional pressure drop. Higher flow rates lead to increased frictional losses, highlighting the importance of fluid dynamics strategies in mitigating sand buildup and improving cleanout efficiency. The transition from laminar to turbulent flow further emphasizes the dynamic nature of cleanout operations. As flow rates increase, the potential for turbulent flow also rises, leading to greater frictional losses and necessitating enhanced operational approaches to ensure reliability and efficiency in the cleanout process.

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