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Improved Cuttings Transport in Horizontal Wells: An Experimental Study Using a Clamp-on Tool for Efficient Hole Cleaning

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Abstract

In horizontal well operations, the prevalence of stuck pipe incidents is largely attributed to inadequate hole cleaning, underscoring the critical need for a thorough understanding of this process to mitigate non-productive time and financial losses. Increasing fluid velocity, the major drilling parameter of hole cleaning, diminishes the formation of cuttings beds in a wellbore. This study primarily centered on the mechanical displacement and removal of solid particles, employing advanced image processing techniques to elucidate the dynamic behavior of solid particles in deviated wellbores. The core objective of this study was to experimentally scrutinize the effects of a downhole clamp-on tool on fluid velocity to improve hole cleaning practices. To address this challenge, a customized flow loop was designed and constructed to accurately replicate the conditions encountered in horizontal wells. Pure water was used to demonstrate the effects of the clamp-on tool on cuttings transport for lightweight drilling fluid conditions. Strategically deployed, the clamp-on tool played a pivotal role in agitating cuttings, mitigating their accumulation at the bottom of the borehole. The tool's agitation mechanism noticeably improved cuttings removal by increasing velocity, extending the perturbation of cuttings transport in the tool's downstream flow, and reducing bedding formation. At lower flow rates, the tool led to an over fourfold increase in average particle velocity within the tool and a twofold increase after the tool. Our results demonstrate the substantial potential of mechanical assistance to address hole cleaning challenges and significantly advance horizontal well operations.

Keywords Cuttings transport · Experimental investigation · Fluid velocity · Horizontal well drilling · Downhole tool · Particle tracking

List of Symbols

AI	Artificial intelligence
ANN	Artificial neural network
BHA	Bottomhole assembly
CFD	Computational fluid dynamics
CTE	Cuttings transport efficiency
DAQ	Data acquisition system
DC	Direct current
ECD	Equivalent circulation density
ERT	Electrical resistivity tomography
FPS	Frames per second
HCF	Hole cleaning factor
LabVIEW	Laboratory virtual instrument engineering workbench
LPT	Lagrangian particle tracking
NI	National Instrument
NPT	Non-productive time
ROP	Rate of penetration
RPM	Revolutions per minute
TDS	Total dissolved solids
VFD	Variable-frequency drive
VI	Virtual instrument
D	Diameter [m]
d_c	Cuttings diameter [m]
ID	Inner pipe diameter [m]
L	Length [m]
OD	Outer pipe diameter [m]

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Q	Flow rate [L/min]
V	Velocity [m/s]
$\overline{v}$	Average particle velocity [m/s]
v_x	Particle velocity in x-direction [m/s]

1 Introduction

As the worldwide energy demand continues to surge, the exploration and extraction of hydrocarbon reservoirs have pushed the boundaries of drilling technology, leading to a surge in the development of intricate and challenging well structures. These complex wells encompass high-angle, horizontal, and extended reach configurations characterized by elongated lateral sections. Together, complex wells represent a new frontier in drilling operations that demand advanced engineering techniques and technologies to navigate the complexities of extraction. Currently, horizontal or directional drilling is used in almost all newly constructed US natural gas and crude oil wells, which doubled the average well footage between 2010 and 2021 [1, 2]. Horizontal and directional wells, with their extended reach, can access more prevalent geological formations, resulting in enhanced productivity. However, intricate well configurations present a significant challenge in the domain of drilling engineering, as the accumulation of drilled cuttings and subsequent inadequate cleaning of the wellbore in the lateral segments of these wells give rise to a multitude of complications. These issues directly affect the wellbore's stability and the overall performance of the drilling process. Tackling these hurdles requires a comprehensive understanding of geological formations and innovative drilling techniques.

For deviated wells, the majority of stuck pipe events are attributed to hole cleaning issues [3], which underscores the fundamental significance of focusing on hole cleaning to mitigate lost time caused by stuck pipe incidents. The disciplines of mechanical, petroleum, and chemical engineering have made several major advances in this area, including improvements in the optimization of wellbore trajectories and advancements in hole cleaning procedures [4]. The subtle interaction between fluid velocity, rotation of the drillstring, and the rheological characteristics of the drilling mud, in conjunction with the attributes of the cuttings, exert key influences on the movement of cuttings in the horizontal segments of wellbores [5–7]. Fine-tuning these factors regulates the load-bearing capacity of drilling fluids and ultimately improves wellbore cleaning. Furthermore, horizontal drilling introduces additional intricacies related to fluid dynamics, hole cleaning, the rheological behavior of the fluid, management of solid particles, and control of equivalent circulating density (ECD).

To tackle these complexities, the incorporation of virtual modeling and dynamic drilling simulators have provided an invaluable understanding of crucial metrics such as the ECD within the wellbore and the height of the particle bed formation [8, 9]. However, these modeling techniques, especially in the absence of actual flow data, can exhibit sensitivity to input parameters and frequently rely on assumptions. Thus, incorporating experimental setups alongside models is crucial, as empirical data can provide invaluable validation for theoretical predictions. Development of laboratory-scaled flow loops enables the simulation of drilling conditions, to facilitate examination of the behavior of cuttings in horizontal wells through image processing techniques [10].

Moreover, the efficiency of cuttings transport and, consequently, hole cleaning in horizontal wells are significantly influenced by the bottomhole assembly (BHA) components. Downhole tools integrated within the BHA, including centralizers and stabilizers, exert control over the flow dynamics. These adjustments augment fluid velocity, facilitating more effective cuttings transport [11, 12]. Recognizing and incorporating recently introduced hole cleaning devices is crucial, as they address the immediate need for efficient wellbore cleaning, cost-effective drilling, and overall performance optimization in highly deviated wells [13]. The application of downhole cuttings removal devices featuring V-shaped blades has significantly improved the efficiency of cuttings transport, as evidenced by a combination of experimental and computational approaches. This offers experts a unique opportunity to explore the functioning of hole cleaning devices under fluctuating conditions [14].

In addition to specialized downhole equipment tailored for stabilizing and centralizing the BHA, there have been developments in tools designed explicitly for hole cleaning, regardless of stabilization or centralization capacity. Downhole drilling tools for cuttings transport can also play a vital role in optimizing the efficiency of the drilling process [15]. The strategic utilization of such devices in drilling horizontal wells has proven highly effective in addressing hole cleaning challenges [14]. These tools play a critical role in facilitating cuttings transport, ensuring effective hole cleaning, and preventing issues such as stuck pipe incidents. Additionally, the advantage of clamp-on tools lies in their independent functionality, as they do not require modifications to the BHA and can be easily clamped onto the drill pipe. The idea of clamp-on tools is to agitate cuttings, enhance their movement, and reduce their accumulation at the bottom of the borehole. The development of such novel tools has emerged as a promising approach to improve the efficiency of cuttings transport. However, despite these advancements, challenges persist, and ongoing research is required to explore refinements in tool designs and their real-time applications.

In this study, we aimed to employ a particle tracking method to evaluate the effectiveness of a clamp-on tool to enhance cuttings velocity and downstream flow. This study seeks to advance our comprehension of the impact of downhole equipment and drilling hardware on hole cleaning by introducing a novel downhole device with a clamp-on mechanism that is specifically engineered to tackle hole cleaning challenges. Our experimental study involves a scaled flow loop setup to replicate real wellbore conditions that incorporate dimensional analysis and detailed design considerations. By utilizing visualization techniques to illustrate particle behavior, we provide valuable insights into the performance of the clamp-on mechanism and its impact on wellbore cleaning efficiency. Overall, we aim to contribute to the ongoing efforts to achieve efficient cuttings transport, reduce nonproductive time (NPT), and enhance the financial outcomes of complex drilling operations.

1.1 Key Parameters in Cuttings Transport

Throughout the past three and a half decades, extensive research has been dedicated to the study of cuttings transport within complex wells. Despite extensive experimental and simulation studies in this domain, there remains ongoing debate and varying outcomes regarding the influence of multiple aspects that impact cuttings transport. Studies in this field predominantly adopt computational analyses, experimental methodologies, and/or simulation-based analyses as key research approaches. These investigations have delved into various influential factors and shed light on critical aspects of the cuttings transport process.

Initial studies on cuttings transport mainly focused on the flow rate and fluid rheology as determining variables of cuttings generated in directional wellbores that are also reasonably straightforward to modify throughout the drilling process [16, 17]. In high-angle and horizontal wells, enhancing the fluid flow rate improves cuttings transport by reducing bed development and promoting turbulent flow, while high-viscosity fluids are less effective due to their hindrance to achieving turbulent conditions [18]. Early research highlighted that the transition from laminar to turbulent flow in horizontal wellbores is a critical factor affecting cuttings transport. This transition is identified by the Reynolds number, which indicates a change in flow characteristics [19]. Subsequently, sensitivity analysis showed that the thickness of cuttings beds is greatly reduced when the annulus velocity is increased by increasing the flow rate [20]. Thus, if the fluid velocity decreases, cuttings accumulation and development of cuttings bedding will be enhanced [21]. Tomren et al. [22] employed experimental methods to investigate the impact of various factors on cuttings transport in horizontal wells, finding higher annular velocities crucial for efficient hole cleaning. In addition, Kelessidis and Bandelis [6] employed both experimental and analytical methods to examine factors influencing cuttings transport in horizontal wellbores, with their research emphasizing the pivotal role of annular mixture velocity in determining efficiency.

Diverse research has reported varying findings regarding the type of drilling fluid as an influencing factor on hole cleaning efficiency, leading to contradictory suggestions on the optimal drilling fluid. Evaluation of the same variables under distinct circumstances might provide an explanation for these discrepancies [17]. For example, Pandya et al. [23] combined experimental and analytical approaches, focusing on rheology and flow rate. Their study revealed that low-viscosity drilling fluids prove more effective in wellbore cleaning, with saltation emerging as the predominant conveyance in horizontal wells. Furthermore, the strategic design of water-based drilling fluids plays a crucial role in enhancing hole cleaning efficiency and maintaining hole stability, leading to improved overall performance in drilling operations [24]. Field practice has confirmed that water-based drilling fluids, optimized for low gel strength and viscosity, enhance hole cleaning but may increase wear on drilling equipment and are more prone to barite sag, while improving the efficiency of solids control equipment [25]. Maintaining a critical fluid velocity is essential for effective hole cleaning in horizontal drilling, particularly when using water-based drilling fluids (demonstrating light drilling fluid), to prevent the formation of a stationary cuttings bed [26, 27]. The emphasis on maintaining critical fluid velocity, particularly in the context of horizontal drilling with lighter fluids, is a key takeaway, highlighting the role of fluid dynamics in preventing the accumulation of cuttings.

Experimental and numerical analyses by Ferroudji et al. [28] underscored the criticality of striking a balance between eccentricity, RPM, flow rate, and the interplay between the flow rate and diameter ratio. Key results from analytical experimentation utilizing univariate and multivariate approaches revealed that drillstring rotation (RPM) is the key operational parameter for cleaning deviated wellbores and works best when combined with flow rate parameters to obtain efficient deviated wellbore cleaning with positive eccentricity [29]. Sun et al. [30] employed both analytical and numerical methodologies and elucidated that augmenting the revolutions per minute (RPM) leads to a substantial reduction in the volume of cuttings. This effect was particularly pronounced at flow rates within the low to intermediate range. Another experimental study considered superficial velocity supplemented by eccentricity as the major factor and found that eccentricity significantly influences flow pattern transitions, indicating its pivotal role in cuttings transport [31].

Other studies emphasize the prominent impact of drillstring rotation, especially as drilling of high-complexity wellbores has escalated in frequency and intensity, making the impact of drillstring rotation increasingly evident. For example, pipe rotation substantially enhances cuttings transport, particularly in eccentric drill string configurations

[32–35]. Werner's [36] experimental research, which emphasized rheology and RPM, highlighted the dominant influence of drillstring rotation on characteristics of fluid dynamics. Experimental, analytical, and numerical approaches established that pipe rotation diminishes the critical fluid velocity required to prevent the formation of a stationary cuttings bed [37]. The impact of drill pipe rotation, particularly whirling motions, improves cuttings transport and hole cleaning in drilling, demonstrating that using water as the drilling fluid significantly enhances this process [38]. Furthermore, CFD analysis supports the idea that drill pipe rotation demonstrates beneficial performance in more eccentric circumstances, since the drill pipe will be closer to the cuttings accumulation [39].

More recently, researchers have established the concept of determining the direct solid's volume fraction by observing solid beddings in the annular region and utilizing the electrical resistivity tomography (ERT) method [40]. In addition, Huque et al. [41] applied an artificial neural network (ANN) approach in experimental and numerical studies, which highlighted that even factors with seemingly minor influences can exert a notable impact on estimations of cuttings transport efficiency (CTE). Similarly, the hole cleaning factor (HCF) allows real-time evaluation of hole cleaning conditions, showing strong correlation with daily drilling reports and identifying potential stuck pipe sections [42, 43]. Recent studies broke new ground by employing the kinetic theory of granular flow and dispersed turbulence model to accurately predict multi-size cuttings transport, accounting for collisions and turbulence interactions [44]. Furthermore, novel approaches employing machine learning techniques have been proposed to estimate the size of drill cuttings [45] and the cuttings bed thickness [46], and another study implemented AI techniques to predict cuttings concentrations [47]. Finally, utilizing machine learning enabled early detection of operational irregularities and enhanced safety by proactively identifying issues and extending response time [48].

2 Materials and Methods

To ensure the utmost productivity and enhancement of deviated well drilling procedures, it is crucial to properly eliminate the solid particles created. In order to gain insights into the movement of drilling cuttings in the framework of horizontal wells, we conducted a comprehensive investigation and evaluation using a graphical representation within a laboratory flow loop setup. This work primarily focused on clarifying the path of particles as they are conveyed through the horizontal annular segment. We employed a flow loop setup, which allows us to faithfully replicate the drilling conditions encountered in horizontal wells. This replication takes into account different RPMs and fluid flow rates, providing real-time data and observations.

2.1 Experimental Setup

This work presents ideas and methods for building a robust experimental framework that supports thorough exploration of hole cleaning. Dimensional analysis, meticulous design, and the building of a customized experimental flow loop setup are all part of this extensive procedure. Our laboratory-scaled flow loop design has three main subsystems: inner pipe (drillstring) rotation, cuttings input, and a data acquisition and control system.

2.1.1 Dimensionless Factor

We constructed an experimental setup, scaled to represent the system, emphasizing the need to devise dimensionless factors to establish a similarity between the experimental design of the flow loop, the tool, and the actual model. Dimensionless factors are employed to unify all aspects of the system, establishing relationships that hold true for "similar" variations, which requires enumeration of all system parameters, including geometry, kinematics, and dynamics.

Geometric parameters are crucial for constructing an experimental setup, so the first step is to identify all system parameters. The following key parameters were determined: diameter of pipe and hole, diameter of beads or cuttings/particles, tool length, and tilt angle. Creating dimensionless factors between the given parameters is the second stage. The system behavior is anticipated to remain unchanged if the ratio between these parameters is preserved when the actual tool is scaled down to the experimental setting.

In terms of geometric factors, if a scaling factor scales down the whole system, these dimensionless parameters should be maintained. Firstly, the ratio between pipe diameter and tool length, d_{pipe}/L, was considered, and secondly, the ratio between pipe diameter and beads or cuttings diameter, d_{pipe}/d_{c}. Accordingly, these considerations enabled the real system's performance to be inferred from the experimental arrangements.

2.1.2 Design

The experimental arrangement features a transparent plexiglass pipe, 3 m in length (L), serving as the test section. This pipe has an inner diameter (ID) of 0.074 m, representing the borehole. Contained within this pipe is a concentric inner pipe with an outer diameter (OD) of 0.04 m, functioning as the drillstring (Fig. 1). The main components of the flow loop are: (1) external assembly for pipe rotation, (2) wellbore, (3) drillstring, (4) flanges to connect additional parts,

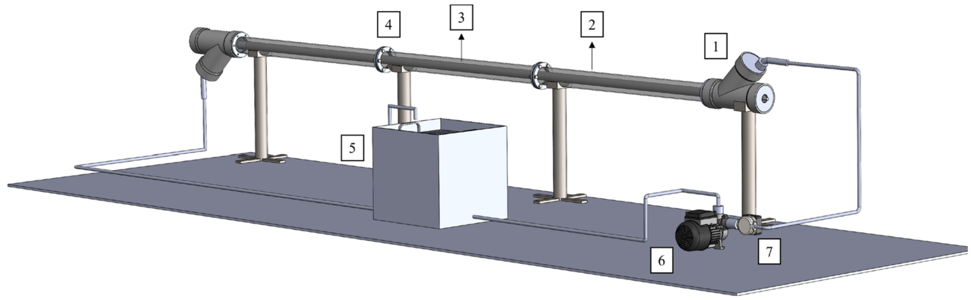

Fig. 1 Elementary horizontal flow loop setup for laboratory investigation. The main components, as depicted, are: (1) external assembly for pipe rotation, (2) wellbore, (3) drillstring, (4) flanges to connect additional parts, (5) fluid tank and cuttings removal, (6) water pump, and (7) flow meter

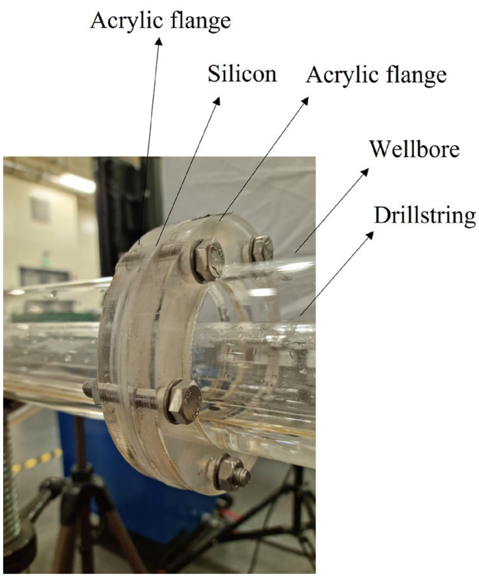

Fig. 2 Acrylic flanges

(5) fluid tank and cuttings removal, (6) water pump, and (7) flow meter.

The plexiglass pipes are manufactured in 1-m lengths and connected to the acrylic flanges with glue that provides high-strength contact and heat resistance (Fig. 2). The transparent plexiglass pipes allow the cuttings transport to be observed and for collecting videos and images. Furthermore, we attached a silicon gasket between the two flanges to prevent air from entering the flow loop and to avoid liquid leaks. The same procedure was followed for each connection in the flow loop.

The fluid tank shown in Fig. 1 has a capacity of 100 L with an agitator of 330 W that provides up to 2000 RPM (revolutions per minute). The sections in the flow loop are connected with PVC pipes of 2 in. The tank was cleaned after each experiment to reduce the accumulation of rust or cuttings.

2.1.3 Drillstring Rotation

The weight and rotation of the inner pipe are supported from the outer part of the flow loop assembly (Fig. 1). Specially designed shafts are installed at both ends of the drillstring and extend outside the main structure. On the outlet side, the shaft is connected through a mechanical coupling to the stepper motor shaft to provide rotation of the drillstring. At the entrance section of the setup, the pipe is unobstructed and is connected to a rotary encoder to measure the rotational speed of the drillstring while conducting experiments. The inner pipe (drillstring) and the stainless steel shafts add additional weight that needs to be supported; thus, ball bearings

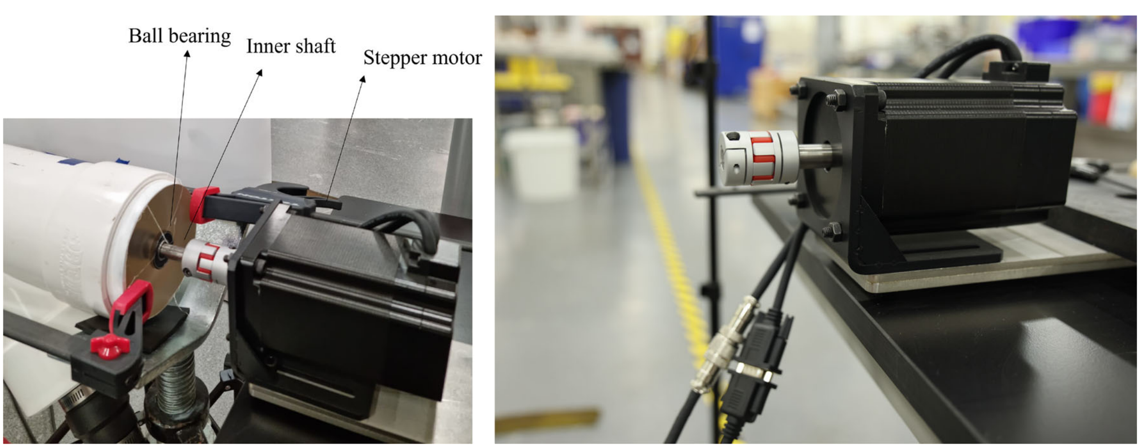

Fig. 3 Inner shaft connected to the stepper motor

Fig. 4 Drillstring, inner shaft connection, and mechanical seal. Mechanical seal design allows pipe rotation

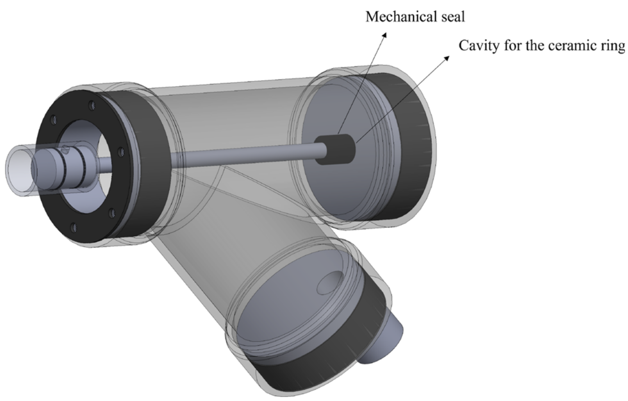

Fig. 5 Assembly for providing drillstring rotation and the mechanical seal for the flow loop setup

are installed on both ends of the assembly. Since fluids are pumped in the flow loop, the ball bearings have a rubber element that significantly reduces the oxidation and friction on the bearing (Fig. 3).

A mechanical seal is placed on both inner shafts to contain the fluid in the flow loop while rotating the drillstring (Fig. 4). The rotating shafts create small openings that fluid can escape from, and thus reduce flow loop saturation with the fluid.

The mechanical seal consists of two main rings, one installed in the rotary shaft while the other one is held stationary in the cavity on the end flange. The load of the strings ensures contact between the rotary and stationary rings. The mechanical seal is activated when stress is applied to the string, allowing it to lock the two rings and provide the primary sealing, as illustrated in Fig. 4. The rotary shaft (Fig. 4) is attached to the inside of the acrylic pipe with two O-rings and screwed in place to provide a secondary sealing. Since the pipe is placed in the emulated wellbore, both ends contain a ceramic ring installed in a cavity, as shown in Fig. 5.

Several components that allow continuous measurements and control of the equipment are illustrated in Fig. 6.

To evaluate the tool's performance, the mechanical clamp-on tool was attached to the drillstring between the two measurement points.

The flow rate is controlled using a water pump (NPY-2051–0538) with a maximum flow rate of 18 L/min. The pump is connected to a single-phase power supply and provides three-phase output. To control the flow rate during the experiments, the water pump is connected to a variable-frequency drive (VFD).

The drillstring rotational speed is measured with an incremental encoder attached to the motor shaft's end. As the encoder shaft rotates, the encoder records the change in position (degrees) compared to the initial state. The output signal is acquired as a waveform and converted to revolutions per minute (RPM). The drillstring rotational velocity is managed through a closed-loop DC motor system via a driver. The encoder is used to obtain specific rotational speeds of 60, 80, 100, and 120 RPM for testing. To enable reliable and robust control of the rotational speed of the DC motor, the driver is connected to an Arduino Uno with a push-button application.

The rotary encoder measurements are gathered through a data acquisition system and analyzed in real-time with a laboratory virtual instrument engineering workbench supplied by National Instruments (NI). The data acquisition system accurately records rotational speed and differential pressure data per second for every sensor included in a flow loop hardware. The data acquisition device is a multifunction I/O USB-6212. Figure 7 illustrates the data acquisition and synchronization virtual instrument (VI). Initially, two virtual channels are used to access all of the analog and digital input channels available for the particular DAQ. To consider the timing parameters, we pass the tasks to the sample clock and create a constant that allows us to change the sampling rate (samples per second). To acquire data continuously, we choose continuous sampling.

The data are visualized in real-time in the front panel of LabVIEW. The fluid tank level is measured and recorded as a constant before starting the test. In addition, the water pump operating frequency, which is converted to flow rate, is added as a constant during the experiments.

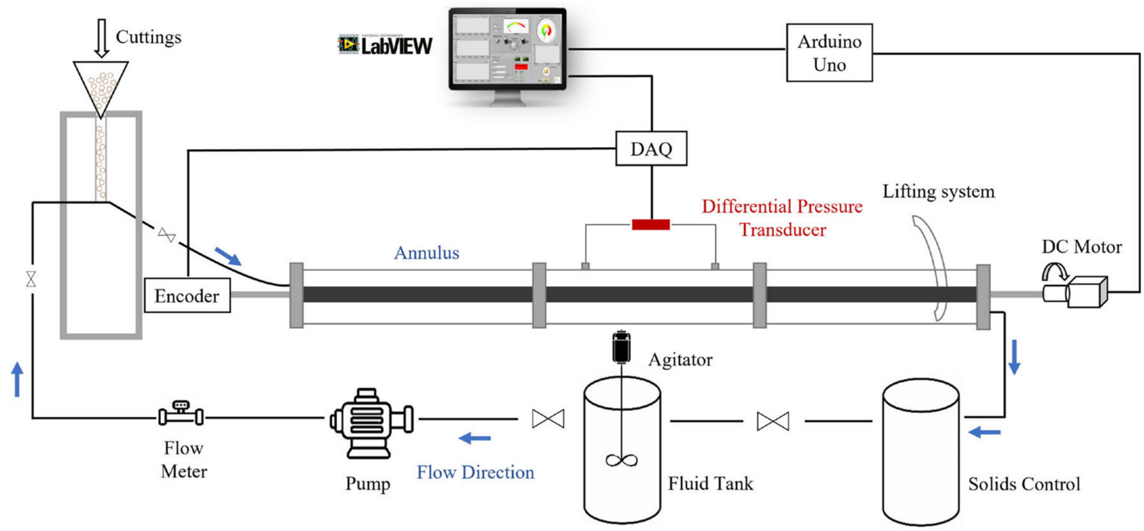

Fig. 6 Schematic diagram of custom-built flow loop setup

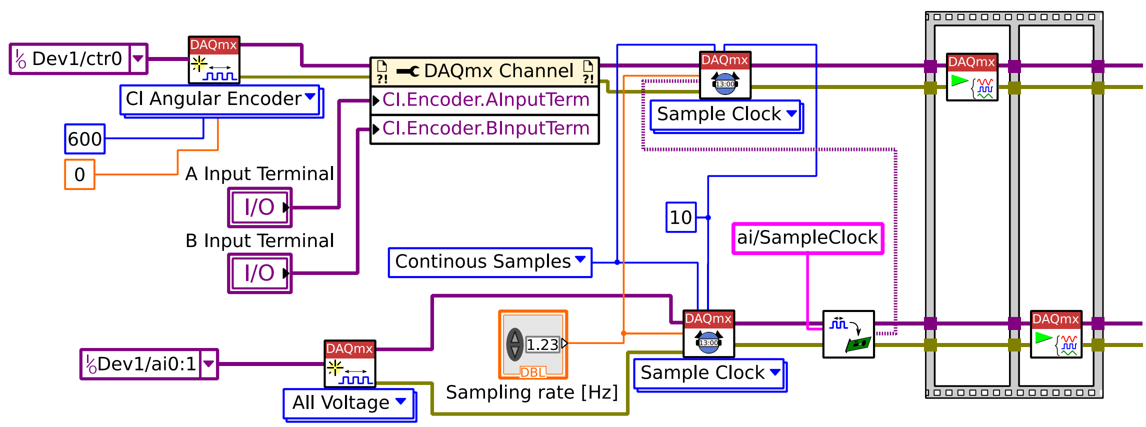

Fig. 7 Data acquisition and synchronization

2.2 Experimental Procedure

After completing the major construction phase, the experimental investigation was conducted and assessed. Several critical components that affect the efficacy of hole cleaning were taken into consideration, during the experimental investigation, including the rotational speed of the drill pipe (RPM), the fluid flow rate, the rheological properties of the drilling mud, the dimensions of the generated cuttings, the flow regime, and the rate of penetration (ROP) [20]. This study primarily centered on the mechanical extraction of accumulated solid particles. The experiments aim to show the formation of particle trajectories and their path of differentiation in order to clarify their actual behavior of cuttings within deviated wells with distinguished lateral sections. These experiments were conducted under differing fluid flow rates and rotations ranging from 60 to 120 RPM (Table 1).

Water was employed to simulate Newtonian fluids, and generated cuttings during drilling operations were depicted and simplified as 5.5-mm (*d*) spherical particles with a density of roughly 1.15 g/cm^3. Generated cuttings tend to accumulate and form beddings once the drilling stops. Therefore, the use of different drilling fluids for wellbore cleaning and drilling operations is advised. When drilling comes to a halt, low-viscosity or water-based fluids work better for cleanout procedures [49]. In this study, pure water was used as the drilling fluid in order to demonstrate the effects of the novel clamp-on tool on cuttings transport under lightweight drilling fluid flow conditions.

At the start of each experiment, the end valve was closed to circulate fluid in the flow loop and fill the wellbore (6), as shown in Fig. 8. In the initial stage, the flow loop contains air while pumping fluid starts to build up the pressure in the system. To eliminate this effect, a relief valve (5) is placed in the end part of the system, which was opened while filling

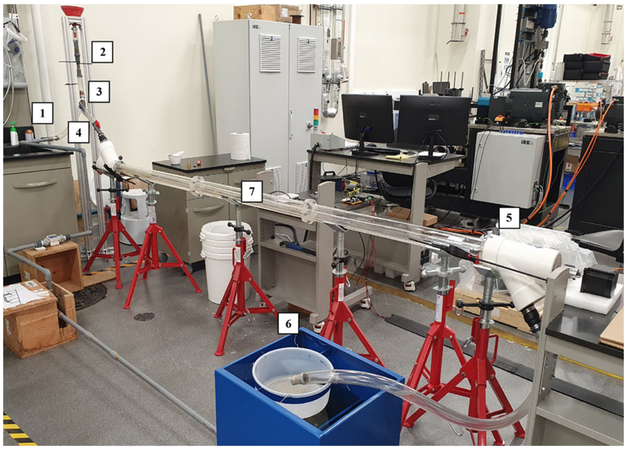

Fig. 8 Actual flow loop design. The main control valves, as depicted, are: (1) entrance valve–fluid, (2) entrance valve–cuttings, (3) entrance control valve–fluid + cuttings, (4) additional safety control valve, (5) relief valve, and (6) end valve. The clamp-on tool is positioned within the central test section and clamped onto the inner pipe (7)

the flow loop and closed while we opened the end valve (6) to achieve full fluid circulation.

Another critical point is the complete filling of the flow loop with a fluid, which corresponds to almost zero air bubbles. To accomplish this, two additional valves (3 and 4) are placed in the entry of the flow loop to regulate the air and the pressure during the experiments. Once the flow loop was filled with the testing fluid, the three valves at the entrance of the equipment were closed (1, 3, and 4) to isolate the wellbore from the entire system. This methodology allows the insertion of water with particles from the conical funnel (2) to be slowly pumped into the wellbore with the assistance of gravity. Once a specific volume of particles has settled, the valves at the entrance (1, 3, and 4) and in the end of the flow loop (6) were opened to initiate the experiments as an open-loop system.

2.3 Downhole Tool

This study focused on exploring the innovative application of a clamp-on tool on cuttings transport, with the aim to advance hole cleaning techniques. By delving into this tool's unique attributes and operational efficiencies, the research seeks to unveil new methodologies and potential breakthroughs in drilling technology, emphasizing both the practical implications and the novelty of this approach in enhancing wellbore cleaning efficiency.

An experiment involving a scaled-down tool was performed. The scaled-down version of the tool, intended for experimental purposes, features dimensions of 0.07 m for the outer diameter and an inner diameter matching the OD of the pipe at 0.04 m. This compact design ensures accurate proportions, making a dependable model for testing and analysis in controlled environments. The tool was placed in the middle test section and clamped onto the inner pipe (7). To further illustrate this concept, visualization techniques were employed to show the velocity of single particles before reaching the tool, while passing through the tool, and after passing the tool downstream. The flow regime of the corresponding flow rates in the annulus space between the outer pipe and inner pipe and outer pipe and clamp-on tool, without inner pipe rotation, was laminar.

2.4 Experimental Investigation

Visual data processing was performed to depict the trajectory of particles in the horizontal flow loop's test section at various points. The velocity and paths of the solid particles were captured using a conventional video camera recording at 50 FPS, allowing reliable tracing of individual particles within the framework.

2.4.1 Particle Tracking

The Lagrangian particle tracking (LPT) technique is a powerful tool for studying non-intrusive fluid flows, meaning it does not disturb the flow. In addition, LPT is versatile, can be used to study a wide variety of flows, and is relatively inexpensive. LPT techniques track the movement of the particles over time using various methods, such as video microscopy or laser tracking. Once determined, particle trajectories can be used to calculate multiple properties of the flow, such as the velocity field, the turbulent intensity, and the Reynolds stress. In this work, complex flow behavior was analyzed using commercially available software created by Stanford University's Environmental Complexity Lab. Operating on the concept of generating deterministic particle's paths within fluids from videos capturing their trajectories, the software leverages this determinism by employing advanced predictive tracking mechanisms to effectively tackle even the most complex tracking challenges [50].

Visual LPT, the main measuring software tool, operates on the notion of tracking the movement of particles introduced to the stream that behave identically to true fluid elements. The first step was to add particles to the flow. The particles were then tracked over time using a video camera to capture images of the particles in a series of time steps. The images were processed to determine the position of the particles in each image. The particle positions were then used to calculate the particle trajectories.

Once determined, the particle trajectories were used to calculate various flow properties. The velocity field was calculated by taking the derivative of the particle trajectories with respect to time. The turbulent intensity can be calculated by measuring the fluctuations in the particle velocities.

3 Results

This study primarily centered on the mechanical displacement and removal of solid particles, employing advanced image processing techniques to elucidate the dynamic behavior of solid particles in deviated wellbores. The aim of this comprehensive data evaluation was to successfully distinguish diverse modes of the movement of solid particles and their corresponding trajectories in order to evaluate the efficiency of a clamp-on tool. A compiled results database was generated after performing experiments for the specified testing framework (Table 1).

3.1 Particle Tracking Analysis and Visualization

In this study, the methodology involved capturing images of particles at various time steps using a video camera. Subsequently, these images were processed using MATLAB to determine the precise positions of the particles in each frame, which were then utilized to calculate their trajectories. The MATLAB functions PredictiveTracker.m and Velocities.m were employed for the analysis of particle behavior. The first function, PredictiveTracker.m, utilizes a video to generate Lagrangian particle trajectories through a triple-frame estimation method (Fig. 9), while simultaneously, the Velocities.m algorithm compiles and displays velocities utilizing the structural arrangement created by the former function [51].

3.2 Application of the Clamp-on Tool

We aimed to investigate and prove the influence of a novel clamp-on tool on hole cleaning for lightweight drilling fluid. Figure 10 summarizes the general results. There was a discernible increase in velocity as soon as the particles reached the tool and followed by a higher downstream velocity relative to the entrance velocity. Consequently, the tool prolongs particle retention in the upper portion of the wellbore, which experiences higher velocity. The results of the experiments are shown in Figs. 10, 11, 12, 13, 14, 15, 16, 17, and 18. These figures illustrate the relationship between flow rate and RPM with particles velocity at different wellbore portions: before the tool, at the tool, after the tool, and downstream the tool. The two flow rates used in this case were 9.8 and 13.2 L/min, and RPMs of 60, 80, 100, and 120, respectively. As can be seen, the relationships between the flow rate and particle's velocity, and between the RPM and particle velocity, are not linear. In general, the higher flow rate, the higher the particle velocity. Similarly, as RPM increases, the particles velocity increases. In addition, we observed that with an increase in fluid velocity within the rotating tool section, there was a corresponding rise in the Reynolds number, as depicted in Fig. 19. This change in fluid dynamics leads to a transition from laminar to turbulent flow. Such turbulent flow conditions are particularly effective in facilitating the transport of cuttings, a critical aspect in horizontal wellbores [17].

Moreover, this research describes how to uninterruptedly follow and monitor a particle's trajectory and rebuild its velocity profile to confirm the practical application of a novel clamp-on tool. The particles velocity increased after the particles entered the tool and was also higher downstream the tool than at the inlet. In summary, when considering lower flow rates, the utilization of the clamp-on device resulted in a remarkable increase in average particle velocity (v_x) within the tool, surpassing a fourfold rise in particle velocity. Furthermore, downstream the tool, the particle velocity exhibited a twofold enhancement compared to its initial state (Fig. 10). This increase in velocity helped to move the particles through the wellbore more quickly and efficiently, which could help to reduce the time and cost of hole cleaning operations. Therefore, we concluded that the proposed mechanically supported downhole clamp-on tool may possibly represent advantageous solution for reducing hole cleaning issues.

Table 1 Experimental testing framework

	Flow rate [L/min]					
	4.6	6.3	8.0	9.8	11.5	13.2
RPM	60					
	80					
	100					
	120					
Fluid	Water					
Particles, d [mm]	5.5					
Inclination [deg]	90					

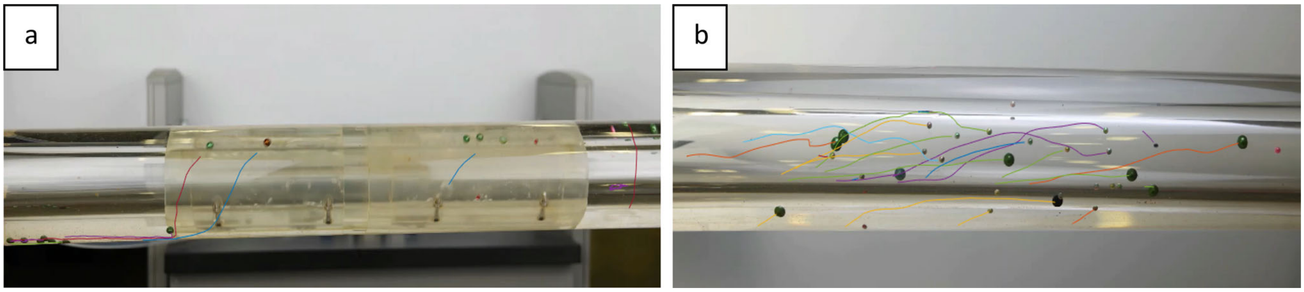

Fig. 9 Particles tracking trajectories from image processing; **a** before and within the tool and **b** downstream the tool

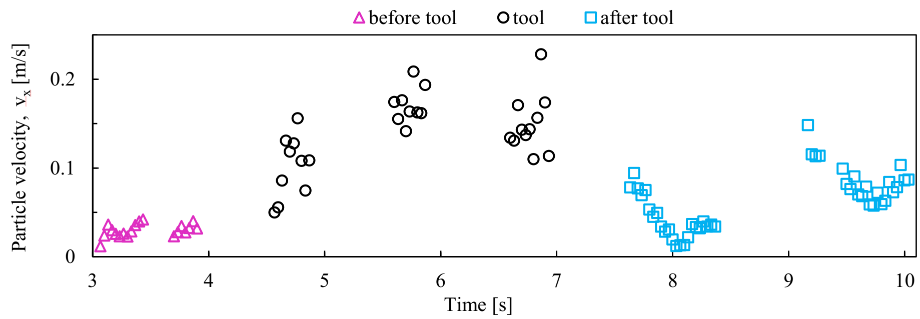

Fig. 10 Particle velocity from image processing; the simplified initial representative results

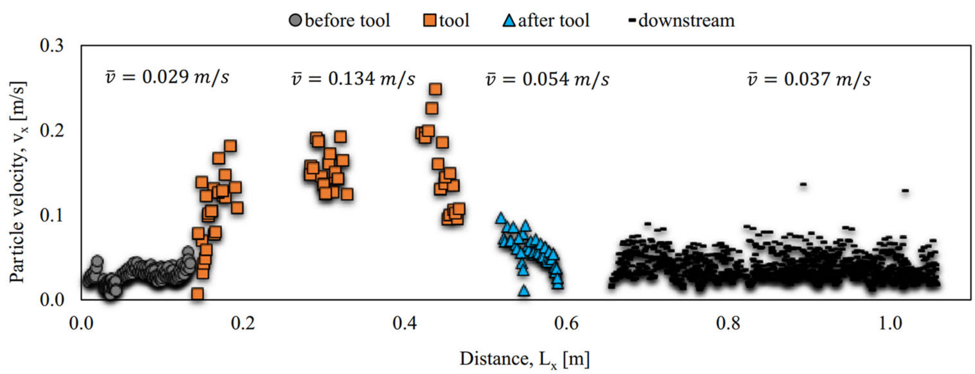

Fig. 11 Average particle velocity ($\bar{v}$) from image processing; for the case of 9.8 L/min and 60 RPM

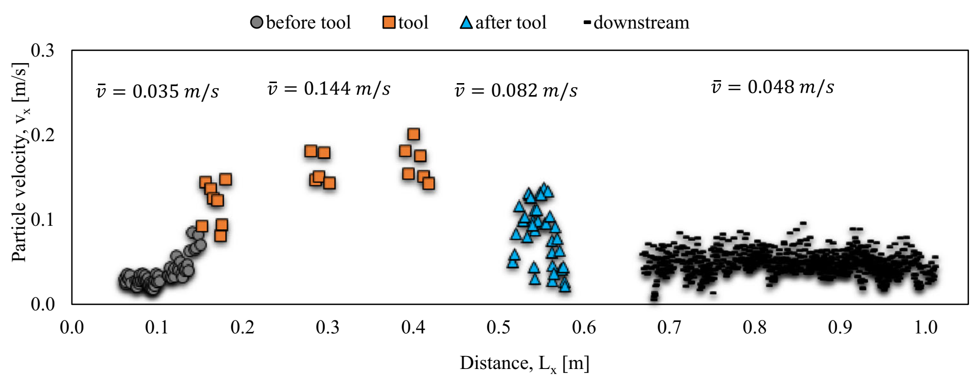

Fig. 12 Average particle velocity ($\bar{v}$) from image processing; for the case of 9.8 L/min and 80 RPM

4 Discussion

The current experimental investigation provides a comprehensive analysis of the effect of a novel clamp-on tool on assisting on hole cleaning. Field applications require more substantial experimental work focusing on enhancing and capturing the effect of the tools more efficiently.

4.1 Non-Newtonian and Viscous Fluids

For these initial experiments, the tested fluid was Newtonian, which differs from the actual drilling applications where the fluid is non-Newtonian. However, the primary focus of the current work was to evaluate the capability of a clamp-on tool to move particles from the lower part of the wellbore

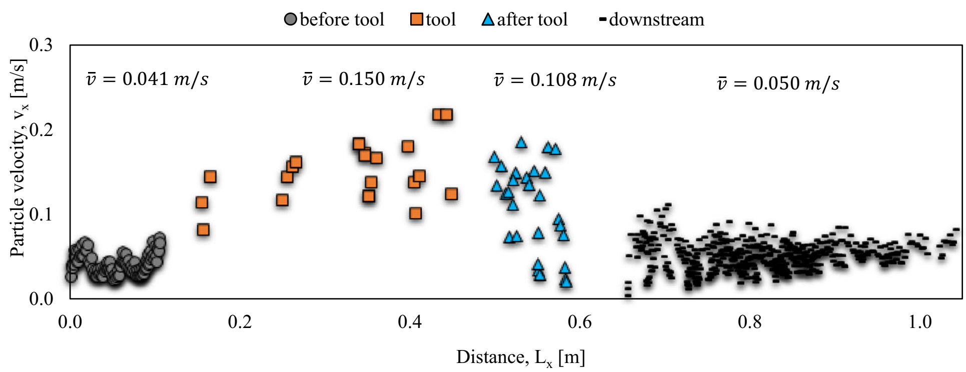

Fig. 13 Average particle velocity ($\bar{v}$) from image processing; for the case of 9.8 L/min and 100 RPM

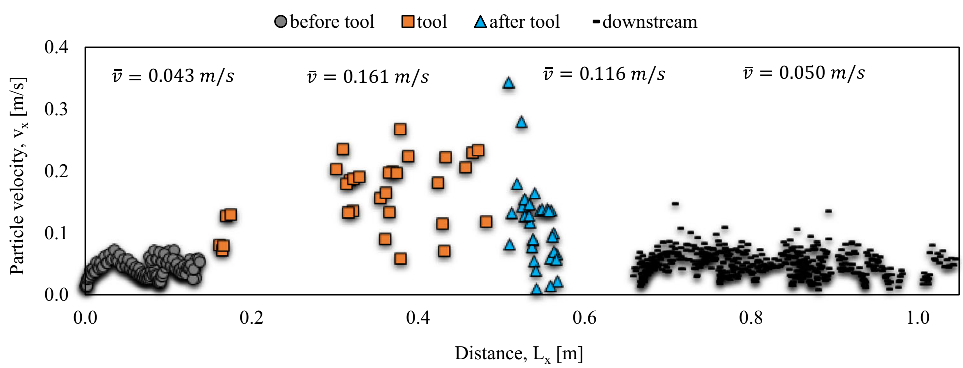

Fig. 14 Average particle velocity ($\bar{v}$) from image processing; for the case of 9.8 L/min and 120 RPM

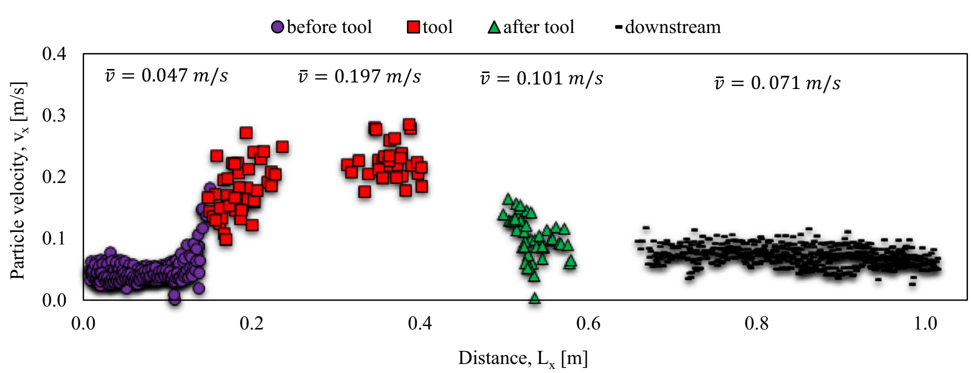

Fig. 15 Average particle velocity ($\bar{v}$) from image processing; for the case of 13.2 L/min and 60 RPM

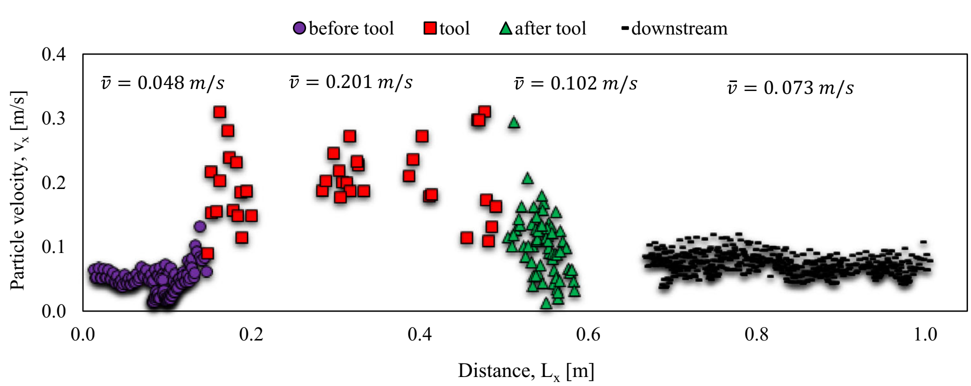

Fig. 16 Average particle velocity ($\bar{v}$) from image processing; for the case of 13.2 L/min and 80 RPM

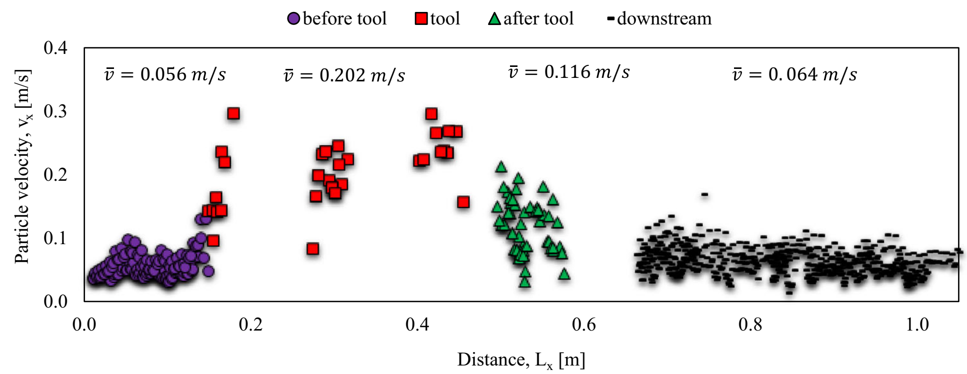

Fig. 17 Average particle velocity ($\bar{v}$) from image processing; for the case of 13.2 L/min and 100 RPM

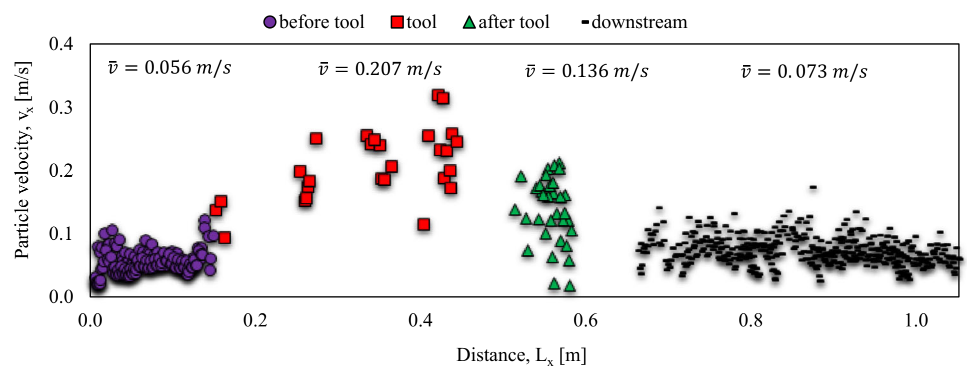

Fig. 18 Average particle velocity ($\bar{v}$) from image processing; for the case of 13.2 L/min and 120 RPM

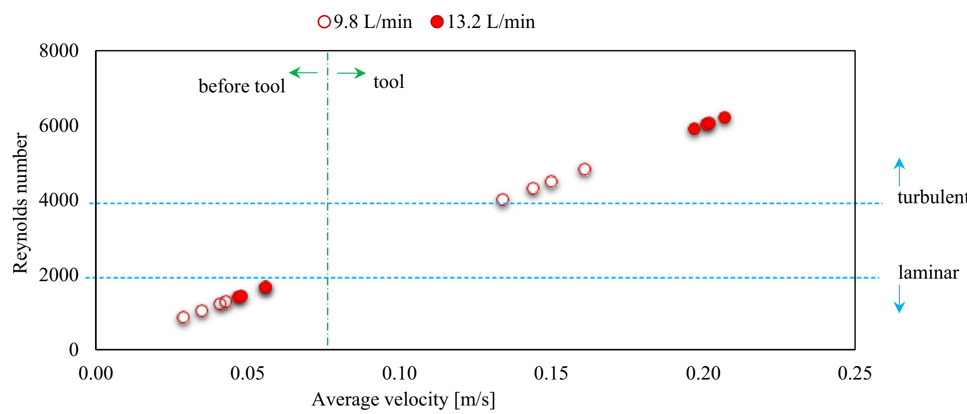

Fig. 19 Correlation between Reynolds number (Re) and average velocity before the tool and at the tool section, considering both flow rates: 9.8 and 13.2 L/min, and at different rotations: 60, 80, 100, and 120 RPM

to the upper part, where the velocity profile is higher. Thus, a transparent fluid was required to capture this effect with a camera to enable particle tracking. Testing a non-Newtonian fluid would decrease the particle settling velocity; therefore, a lower number of cuttings would settle on the lower part of the wellbore. Nonetheless, the operational procedure and working principle of the tool remain consistent under both Newtonian and non-Newtonian fluids, since drilling is a dynamic process, and in operations where fluid circulation is stopped, cuttings will fall in the wellbore. Overall, the results of this study highlight the impact of the clamp-on tool on the cuttings transport and perturbations in downstream flow, demonstrating decreased bedding formation and enhanced particle velocity.

Considering the rheological properties of the drilling fluid, two variables will affect the velocity profiles: plastic viscosity and gel strength. During a dynamic process, i.e., pipe rotation, the drilling fluid shear stress changes and thus influences the plastic viscosity. As the plastic viscosity decreases, the pressure drop across the tool also decreases, which influences the ECD. The clamp-on tool is specifically designed to be utilized in wells where wellbore cleaning- associated problems are encountered. Therefore, the utilization of the tool lowers the ECD on specific sections (since it assists in wellbore cleaning), and the analogous influence of drilling fluid properties is balanced. The observations from Figs. 10, 11, 12, 13, 14, 15, 16, 17, and 18 reveal that the average velocity is notably higher than that measured before the tool. In a similar scenario, if the tested fluid had higher viscosity, this distance could be scaled with a greater factor, and the influence of viscous fluid would have a positive impact on hole cleaning.

4.2 Cuttings and Fluid Density

The experimental framework was operated under the assumption that we had a uniform shape, size, and density of cuttings similar to the working fluid. This work aimed to establish a foundation for utilizing the LPT to evaluate the performance of downhole tools in cases where fluid flow occurs. The working principle of the utilized algorithm is limited to the factor that the tested fluid and particles have the same degree of density. Conventional measurements that utilize differential pressure transducers and total dissolved solids (TDS) to evaluate a tool's or a fluid's performance on wellbore cleaning provide overall good guidance. However, it is challenging and limited to elucidate the dynamic behavior of cuttings in deviated wellbores and in regions close before and after a tool.

4.3 Design and Practical Aspects of the Clamp-on Tool

The main factor affecting hole cleaning in wellbores is the fluid velocity, due to its direct relation with the shear stress on the cuttings bed. If a cuttings bed exists inside a wellbore, an increase in the fluid velocity will erode the bed significantly. However, depending on the drilling conditions, very high fluid velocities may be needed to remove the cuttings bed and may not be applied due to hydraulic and physical limitations. Using the proposed tool increased the velocity of the fluids at the same flow rate and may thus prevent the development of a stationary cuttings beds. Importantly, the tool retains the disturbed particles in the area of higher fluid velocities, which is crucial for obtaining efficient cuttings transport and, therefore, hole cleaning.

The innovation behind our proposed method lies in the utilization of a unique downhole tool with a clamp-on mechanism, which offers a new approach to improve cuttings transport in horizontal wells by actively agitating within the wellbore. Moreover, this innovative clamp-on mechanism offers the advantages of effectiveness, simplicity, cost-efficiency, and suitability for diverse drilling operations. The scalability of our clamp-on mechanism enables the tool to be adapted to different wellbore sizes and drilling environments, ensuring effective utilization without performance compromise.

In comparison, spiral groove heavyweight drill pipes are designed to promote efficient cuttings transport with spiral grooves, to improve drilling efficiency, and to reduce issues like stuck pipes. However, they are costlier, heavier, and less durable in abrasive environments than the proposed clamp-on tool, and present compatibility and manufacturing complexities. Future developments may enable the novelty of the clamp-on tool for cuttings agitation and transport to become even more pronounced, especially when contrasted with spiral groove heavyweight drill pipes. Clamp-on tool confirms the expanding potential of new downhole tools to tackle hole cleaning challenges through mechanical assistance. Notably, when tested at higher flow rates, the prospect of an active blade section in these tools is poised to significantly expand our current understanding and application of drilling technologies. Such innovations toward more dynamic and responsive drilling tools are in contrast with the static design of spiral groove heavyweight drill pipes. Thus, forward-looking approaches in downhole tools hold promise as adaptable mechanical innovations to enhance drilling efficiency and addressing long-standing operational challenges in the oil and gas industry.

5 Conclusions

Advanced wellbore cleaning, through enabling efficient cuttings transport, substantially influences the expenses and environmental footprint of drilling operations. Drilling performance can be improved by lowering non-productive time and associated expenses, which is accomplished by optimized drilling due to improved wellbore conditions, i.e., wellbore cleaning and quality. By using image processing techniques, this experimental study shows the dynamics of solid particles with various configurations as they move in horizontal wells. The study included deriving the velocity distribution and constantly monitoring the particle's trajectory to confirm the efficiency of a previously designed clamp-on device's technique. The following are concluded:

1. The tool effectively increased the particles velocity, which helped move the particles through the wellbore more quickly and efficiently.
2. Sophisticated LPT imaging methods substantiated the concept of the proposed clamp-on downhole device, demonstrating its effectiveness in enhancing cuttings velocity both within the tool and in the subsequent flow, i.e., downstream.
3. The unique geometric attributes of the clamp-on tool noticeably increased cuttings removal and extended the perturbed cuttings transport in the tool's downstream flow. However, it is clear that the increase in the flow rate would eventually diminish returns from the increase in rotational speed, which allows the tool to support the hole cleaning process.
4. Rotation of the drillstring confirms as an essential component in achieving optimized wellbore cleaning. This

dynamic action plays a vital role in ensuring the effective removal of cuttings and thereby enhances the drilling process as a whole.

5. This study confirms that turbulent flow developed within the rotating tool more effectively transports cuttings in horizontal wellbores than laminar flow. The turbulent flow creates a more dynamic fluid environment that helps lift and transport cuttings more efficiently, reducing the risk of cuttings beds formation.
6. This study not only corroborates the potential of new downhole tools to address hole cleaning challenges through mechanical assistance, but also suggests a future direction for these tools. Implementing an active blade section, with its rotary speed driven by the flow rate, would help maintain consistent results across various flow rates. Testing such an active blade section at higher flow rates could significantly enhance our understanding of cuttings transport and help bridge the current body of knowledge.

5.1 Limitations and Future Work

The current study provides a novel experimental framework to evaluate the transport capacity of a downhole tool. Despite the promising results, several limitations can be raised concerning the feasibility of the tool under actual downhole conditions. The following tests are planned to precisely evaluate the tool's efficiency in hole cleaning:

- *Circulation of different volumes of cuttings.* The volume of cuttings will affect the performance of the tool. Such variations will require the evaluation of the differential pressure across the tool and the generated torque. These measurements should be implemented to observe torque and differential pressure changes and correlated with the LPT.
- *Size and shape of the drilling cuttings.* The current study assumes cylindrical cuttings. It is noteworthy that particle shape and size influence packing density when settling at the bottom of the wellbore. Furthermore, the impact of pipe rotation differs based on the size of the cuttings. The experimental parameters could be adjusted to maintain a consistent cuttings density with the drilling fluid but to vary the shape and size of the cutting.
- *Increase the fluid viscosity of a range of actual drilling fluids.* Xanthan gum, a common additive in fluid mechanics experiments, could be used to enhance fluid viscosity while maintaining transparency to enable the utilization of the current particle tracking methodology.
- *Test conventional water-based and oil-based drilling fluids.* The key element of efficient cuttings transport is the rheological properties of the drilling fluid. Future experimental frameworks should focus on combining an innovative downhole design and actual drilling fluids to evaluate the height of the cuttings bed in the horizontal setup.
- *Testing in eccentric configurations.* Despite the experimental setup featuring a concentric drillstring, which may not perfectly replicate real-case conditions, it is important to acknowledge that pipe rotation significantly enhances cuttings transport, especially in eccentric configurations. Therefore, in an eccentric annulus, the impact of the clamp-on tool on cuttings transport is expected to be further amplified.

Recognizing the discrepancies between the experimental setup and actual field conditions opens avenues for future work to explore the effects of eccentricities in the wellbore on cuttings transport efficiency. Investigating these aspects can provide valuable insights into optimizing drilling operations under realistic conditions, and ultimately enhance the effectiveness and accuracy of drilling optimization strategies.

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Declarations

Conflicts of interest The authors declare no conflicts of interest.

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