

Article

A Novel Automated Model for Evaluation of the Efficiency of Hole Cleaning Conditions during Drilling Operations

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Abstract: Hole cleaning for the majority of vertical and directional drilling wells continues to be a substantial difficulty despite improvements in drilling fluids, equipment, field techniques, and academic and industrial research. Poor hole cleaning might cause issues such as stuck pipe incidents, drilling cuttings accumulation, torque and drag, the erratic equivalent circulating density in the annulus, wellbore instability, tight spots, and hole condition issues. In order to enable the real-time and automated evaluation of hole cleaning efficiency for vertical and directional drilling, the article's objective is to develop a novel model for the cutting transport ratio (CTR_m) that can be incorporated into drilling operations on a real-time basis. The novel CTR_m model provides a robust indicator for hole cleaning, which can assess complications and enhance drilling efficiency. Moreover, the novel CTR_m model was successfully tested and validated in the field for four wells. The results of the real-time evaluation showed that the novel model was capable of identifying the hole cleaning efficiency in a normal drilling performance for Well-C and a stuck pipe issue in Well-D. In addition, the novel CTR_m improved the rate of penetration by 52% in Well-A in comparison to Well-B.

Keywords: cutting transport ratio; vertical and directional drilling wells; hole cleaning efficiency; real-time evaluation; enhanced rate of penetration



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1. Introduction

Ineffective wellbore cleaning results in the accumulation of cuttings in the wellbore, causing serious problems that can be costly to remedy, many times greater than the cost of preventive measures to improve wellbore cleaning [1–3]. One of the most widespread problems, caused by cuttings accumulation which leads to stuck pipes in a wellbore, is a mechanical stuck borehole (about 30% of all stuck boreholes in vertical wells are connected to a hole cleaning problem; in high-angle wells, this rate is more than 80%) [4]. The efficiency of cuttings removal with increasing wellbore length is determined by many parameters, but the quality of wellbore cleaning mainly depends on the combined effect of the technological parameters of the used equipment and in particular the hydraulic parameters of hole cleaning (the rheology of the drilling fluid, pressure losses in different parts of circulation system, the type of flow, etc.). The key function of any drilling fluid is to clean the borehole by continuously transporting cuttings from under the bit to the surface [5,6]. The determinants of cuttings' transport, in turn, are the drilling fluid itself and the cuttings' velocity, which depends on the drilling fluid velocity. Mud velocity depends on the rheological parameters of the fluid, its density, pump capacity, and the geometry of the borehole annulus. Mud velocity appears to be a determining factor in wellbore clean-up. It could be possible to create a velocity that removes all the cuttings entering the well, but there are conditions in the well where the window between pore pressure and wellbore wall fracture pressure may be narrow, resulting in the fracturing and absorption of drilling fluid, and the wellbore walls may be subject to abrasive sludging. Such points make wellbore

clean-up monitoring difficult [7,8]. The factors affecting wellbore clean-up are divided into three groups. The first group includes the fluid flow rate and the fluid parameters such as the viscosity and density. Furthermore, these parameters are interdependent and can influence the behavior of a moving fluid. For example, the viscosity of a fluid refers to its resistance to flow and can influence its flow rate through a pipe or annulus. Assuming all other parameters remain constant, a fluid with high viscosity will flow more slowly than a fluid with low viscosity. Similarly, a fluid's density can impact its flow rate. A fluid with a higher density will require greater pumping force to move through a pipe or annulus, resulting in a delayed flow rate [9,10]. The second group consists of the cuttings' parameters, which include the cutting density, size, and shape as well as the cuttings concentration in the annulus. The third group is operator factors and consists of the characteristics of the drill string with fluid swirl devices and its eccentric position in the wellbore, as well as the inclination of the wellbore itself. More importantly, optimizing the impact of these parameters can help sustain the carrying capacity of drilling fluids, leading to the improved design of wellbores [2,11]. Moreover, in order to understand the factors that determine the effectiveness of hole cleaning, several studies have been carried out over the years. For instance, Allawi et al. proved that the rotation of the drill pipe is one of the most important parameters for cuttings' removal especially in laminar flow and transition flow [12]. Moreover, over the past few decades, numerous researchers have explored cuttings' transport and developed various mechanistic and semi-mechanistic models to explain flow characteristics [13–15]. Zeidler et al. examined particle settling velocity, flow rate, fluid viscosity, and internal pipe rotation's influences on transport mechanisms within a 15 foot-long, 3.5 inch inner diameter vertical glass tube laboratory setup [16]. Gavignet et al. developed an early mechanistic model for cuttings' transport [17]. Saeid et al. used numerical simulations to analyze 3D incompressible non-Newtonian drilling mud flow in a vertical well drilling model under steady flow conditions, focusing on laminar flow with a Reynolds number of 1150 based on the hydraulic diameter of the annular space [18]. Osgouei et al. performed experiments with a multiphase flow loop, varying air and water flow rates and introducing cuttings into the annulus in different quantities. Data were collected under steady-state conditions, including liquid, gas, and cuttings' injection rates, frictional pressure drop, local pressures, and high-speed digital images to identify the solid, liquid, and gas distribution within the wellbore [19]. Van et al. proposed a new drill pipe design with integrated hydro-mechanical features in each tool joint to address the limitations of mechanical hole cleaning devices (MCDs) in small diameter holes and to extend hydro-clean drill pipe applications to extended reach drilling (ERD) wells [20]. Mohammadsalehi et al. presented a comprehensive combination of Larsen's model and Moore's correlation to estimate and determine the minimum flow rate required for cuttings' removal across all inclination angles, ranging from 0° to 90° [21]. Recently, Mahmoud et al. developed a new parameter, the hole cleaning indicator, which is based on the cutting carrying index (CCI). This innovative model considers various factors such as drilling fluid rheology, density, flow rate, hole size, drill pipe size, hole inclination, and the rate of penetration (ROP) to predict the hole cleaning condition during drilling [11]. The novel model could assist drilling engineers in mitigating issues such as cutting accumulation and drill pipe sticking. Furthermore, the model's predictability was compared to commercially available software, and the results showed a good match [11]. However, when it comes to hole cleaning in drilling operations, there seems to be a significant gap in real-time evaluation methods to effectively test and optimize performance models.

Therefore, in view of the above, the aim of this study is to present the numerous hole cleaning indicators, which determine the nature and extent of borehole cleaning when drilling vertical wells, deviated wells, and wells with horizontal termination, and to show the existing parameters used to develop a novel cutting transport ratio for enhancing the drilling performance and continuous monitoring and assessment of hole cleaning in real-time during drilling.

2. The Mechanism of Hole Cleaning for Different Well Profiles

It is possible to improve the cleaning quality of a vertical borehole by reducing the final settling velocity of the cuttings. However, as the zenith angle increases, the reduction in the final settling velocity contributes less and less to the cleaning quality (Figure 1a). The sludge transport efficiency has to be corrected, because only the axial component of the final settling velocity is taken into account. It is therefore more difficult to predict the cleaning quality in such cases [22]. When predicting and controlling well cleaning, the formation of cutting layers has to be taken into account. Because of this, the volumetric concentration of the cuttings increases [23,24]. Moreover, in the process of deviated well drilling, problems often arise with bottom hole cleaning and the removal of broken rock to the surface due to the deposition of rock particles on the bottom hole or the borehole walls under ineffective cleaning modes. The efficiency of borehole cleaning from cuttings depends not only on the main hydrodynamic indicators and technological parameters of the drilling regime but also the geometry of the annular space and the borehole profile. In turn, the geometry of the annular space is often determined by the eccentric position of a drill string in a wellbore, and the borehole profile is determined by the zenith angle [24]. More importantly, the transport of cuttings has a significant influence on extended reach drilling. Cuttings created in horizontal wells often settle on the bottom side of the annular section. A stagnant cuttings bed will develop if the cuttings are not sufficiently cleared. This may result in a number of operating problems, including high torque and drag, low penetration rates, clogged pipes, lost circulation, and well control problems. Drilling activities must thus be halted sometimes for specific hole cleaning procedures, adding to the amount of unproductive time (Figure 1a) [25–27]. Figure 1b shows that holes with inclinations between 35 and 60 degrees are more difficult to clean compared to near-vertical sections, which are the easiest to clean.

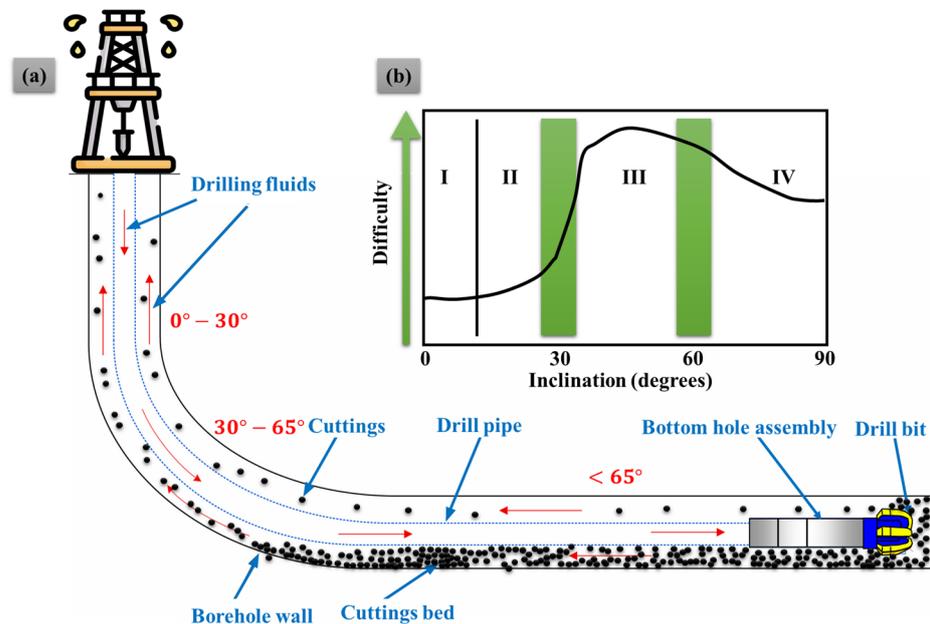


Figure 1. Schematic of transport cutting: (a) shows the transport of cuttings in a horizontal well, and (b) shows the difficulty of hole cleaning in relation to inclination.

Moreover, various classifications of borehole zenith angles are known, affecting the degree of clearance of the drilled rock particles. In mechanical cuttings' removal, the mud behaves differently depending on the zenith angle (Figure 2). In intervals with zenith angles up to 30°, at significantly higher velocities (zone 1), the cuttings are effectively carried away by the mud flow and no sediment is formed on the walls. At lower velocities (zone 3), cuttings are slowly carried away. At zenith angles greater than 30°, the cuttings are deposited on the bottom wall of the borehole. At lower velocities (zone 4), the deposited

cuttings are mixed upwards as a single mass, while in turbulent mode (zone 2), they rise on the contact surface of the cutting]with the drilling fluid in the form of dunes. Conditions corresponding to zones 1 and 2 are ideal for cleaning the cuttings from the borehole. The conditions corresponding to zone 5 guarantee the occurrence of tool puffs, as there is no cuttings' outflow at low rates of upward flow. As can be seen, cutting outflow is more difficult with an increasing zenith angle and lower flow velocity in the annulus. The greatest difficulties arise at zenith angles from 30 to 60°, as under these conditions, the deposited cuttings tend to slide down the borehole and form plugs [24,28].

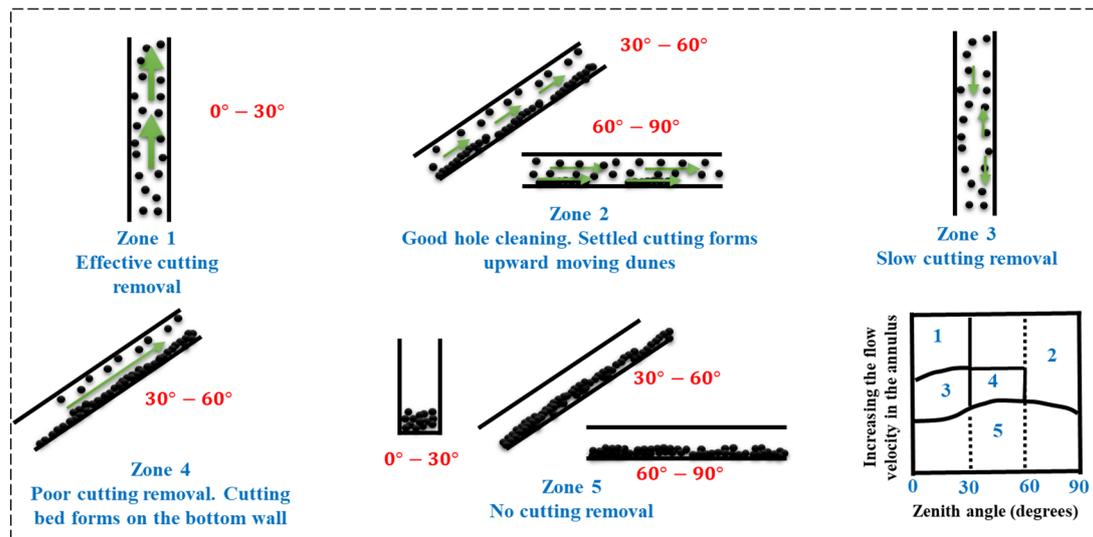


Figure 2. Cutting transport mechanism for different ranges of zenith angle at different speeds in the annulus.

The Hole Cleaning Indicators

In drilling operations, hole cleaning indicators are essential because they track how well the drilling fluid removes drill bits cuttings and keeps the wellbore free. Pump pressure, mud returns, ROP, temperature, torque, and drag are some of these indications. A rapid rise in pump pressure or a drop in mud returns might signal ineffective hole cleaning, and an increase in temperature, torque, and drag can all point to ineffective cuttings removal [29–31]. Drilling experts may take remedial action to avoid problems such as clogged pipes, lost circulation, and wellbore instability by keeping an eye on these signs, ensuring the drilling process runs smoothly and effectively. Several works have studied the hole cleaning indicators. For instance, Sanchez et al. showed that when drilling directional wells, the drill pipe's dynamic behavior significantly contributes to better hole cleaning [32]. Saasen et al. proved that a sufficiently large annular frictional pressure loss is required to obtain proper hole cleaning in deviated wells [33]. Reda et al. proved that the hole cleaning efficiency enhances as the average annular velocity (AV), yield point (YP), plastic viscosity (PV), drill string rotation, and density of drilling fluid increase [34]. Moreover, Abbas et al. proved that the drill string eccentricity and flow rate are the drilling operation characteristics that have the most favorable effects on the cuttings transport procedure [35].

In drilling operations, real-time hole cleaning monitoring is essential for spotting possible problems including cuttings' build-up and accidents involving trapped pipes. However, the quality of the data provided by the rig sensors has a significant impact on the dependability and accuracy of real-time hole cleaning indicators. Conventional rig sensors may not always be adequate to give the data required to run certain models in real-time, which might restrict drilling teams' ability to quickly alter course to avoid or reduce hole cleaning issues [22,36]. More importantly, real-time parameters are those that are altered while drilling is taking place. Surface operating characteristics including ROP, flow-in, revolutions per minute (RPM), open hole diameter (OH), weight on bit (WOB), and others

are affected by these changes. Depending on how real time is defined, there may or may not be a difference between real-time and non-real-time parameters. Figure 3 illustrates the use of iterative steady-state modelling with real-time parameters as inputs while drilling in real-time. This strategy aided in the development that is detailed below.

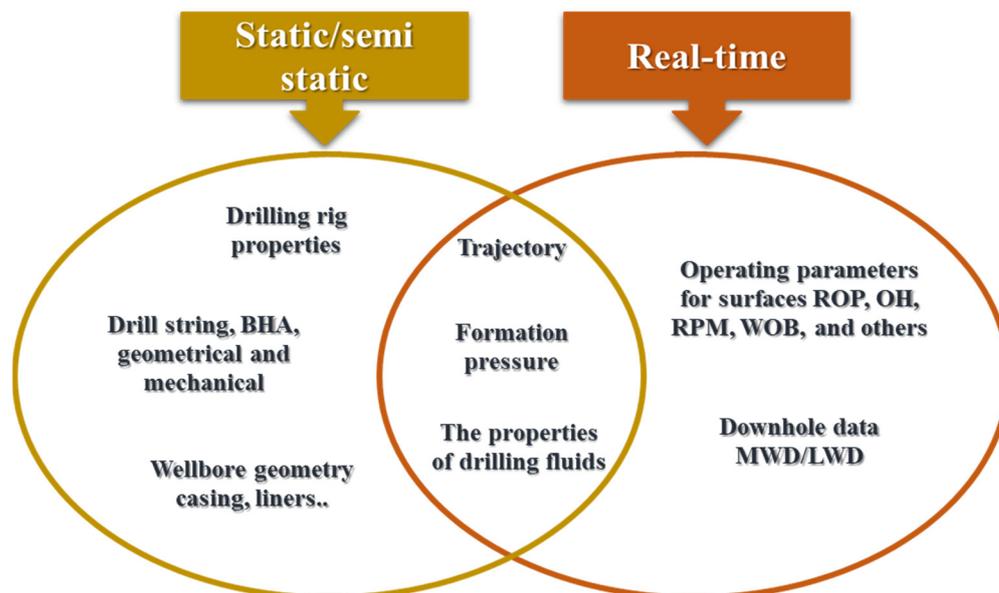


Figure 3. The use of iterative steady-state modelling with real-time parameters as inputs while drilling in real-time.

Thus, the next section explains a novel model which shows the existing parameters used to develop a novel cutting transport ratio for enhancing the drilling performance and continuous monitoring and assessment of hole cleaning in real-time during drilling.

3. Development of a Novel Model Cutting Transport Ratio

The cutting transport ratio (CTR) of the cuttings created by this study serves as the foundation for the innovative real-time indication of the progress of hole cleaning, which was developed by Tom Sifferman in 1974 and was used to assess how well the drilling fluid removes cuttings from the wellbore and was determined as the fluid transport velocity divided by the average mud annular velocity in a lab experiment [37]. The design of his experiment involved investigating various controlled variables. During his observations, it was discovered that some variables were more significant than others. Specifically, it was found that the average velocity and the rheological properties of the mud were the top two factors that affected the transport ratio, although the size of the simulated chips and the density of the mud also played important roles. Typically, the speed at which the cuttings move upwards differs from the velocity of the mud flowing in the annular space. This disparity indicates a tendency, particularly in turbulent flow, for the cuttings to slide back down the hole [37]. The researcher established a connection between the two speeds, which can be expressed as [37]:

$$V_C = V_a - V_s \quad (1)$$

where the symbol V_C refers to the upward velocity of the cuttings, while V_a (AV) represents the average velocity of the mud flow. On the other hand, V_s denotes the downward velocity at which the cuttings slip. To calculate the cutting transport ratio (CTR), both sides were divided by V_a .

$$\text{CTR} = 1 - \frac{V_s}{V_a} \quad (2)$$

Moreover, Sifferman defined the transport percentage as achieving complete hole cleaning when the cuttings and mud reached the surface at equal speed. If there was any

delay in the amount of cuttings that reached the surface or if they arrived later than the mud, the transport percentage would be less than 100%. It is important to note that a CTR of 75% or higher is considered sufficient [37]. Additionally, having an excessively high CTR (above what is required for complete hole cleaning) can be detrimental. It results in reducing the equivalent circulating density (ECD), increasing penetration rates, and, overall, optimizing the efficiency of energy. However, the CTR was only tested in a vertical interval and investigated by the experiment design. Therefore, there is a need to develop a novel model that can be used for real-time evaluations and applied in various profiles, such as deviated and horizontal wells [37,38]. Thus, the novel model transport ratio (CTR_m) was developed starting from the effective mud weight (MW_{eff}) calculated using Equation (3) [22,39].

$$MW_{eff} = MW \cdot CCA + MW \tag{3}$$

where MW is the static drilling fluid density (lb/cf) and CCA is the cuttings concentration in an annulus as defined by Equation (4) [22,39].

$$CCA = \frac{ROP \cdot OH^2}{1471 \cdot GPM \cdot TR} \tag{4}$$

where ROP is the rate of penetration (ft/hr), OH is the hole size diameter (inch), 1471 is the conversion factor, GPM is the pump flow rate (gal/min), and TR is the transport ratio, which can be replaced with 0.55 according to [39]. Furthermore, the ECD is determined based on the MW_{eff} in real time (ppg). To be precise, Equation (5) can be utilized to calculate the ECD [22,39].

$$ECD = MW + \left(\left(\frac{0.085}{OH - OD_{pipe}} \right) \cdot \left(YP + \frac{PVV_{ann}}{300(OH - OD_{pipe})} \right) \right) \cdot 7.481 \tag{5}$$

where OD is the outer diameter of the drill pipe (inch), PV is the plastic viscosity (CP), YP is the yield point (cP), and V_{ann} is the annular velocity of the drilling fluid (ft/min) as defined by Equation (6).

Equation (6) is used to determine the V_{ann} [40]:

$$V_{ann} = \frac{24.5GPM}{OH^2 - OD_{pipe}^2} = V_{cr} + V_{sc} \tag{6}$$

where V_{cr} is the cutting rise velocity (ft/min), which can be calculated by Equation (7), and V_{sc} is the cutting slip velocity with the effect of rate of penetration (ft/min), which can be obtained from Equations (6) and (7) V_{sc} = V_{ann} - V_{cr} [41,42].

$$V_{cr} = \frac{60}{\left(1 - \left(\frac{OD_{pipe}}{OH} \right)^2 \right) * \left(0.64 + \frac{18.16}{ROP} \right)} \tag{7}$$

$$V_{sc} = \frac{24.5GPM}{OH^2 - OD_{pipe}^2} - \frac{60}{\left(1 - \left(\frac{OD_{pipe}}{OH} \right)^2 \right) \left(0.64 + \frac{18.16}{ROP} \right)} \tag{8}$$

In Equation (7), V_{cr} represents the rate at which cuttings are produced and elevated with the mud as a result of the ROP. Equation (9) is used to determine the apparent viscosity of the drilling fluid [42]:

$$M_{App} = \frac{2.4V_{ann}}{OH - OD} \left(\frac{2n + 1}{3n} \right)^n \left(\frac{200K(OH - OD)}{V_a} \right) \tag{9}$$

where the drilling fluid's K is a consistency factor (cP) and the flow behavior index is n , which can be obtained by the Equations (10) and (11), respectively [40,43].

$$k = ((PV + YP))(510)^{1-n} = k_m = ((PV + YP) - (LSYP))(510)^{-n_m} \tag{10}$$

$$n = 3.32 \log \left(\frac{(2PV + YP)}{(PV + YP)} \right) = n_m = 3.32 \log \left(\frac{(2PV + YP) - (2R3 - R6)}{(PV + YP) - (2R3 - R6)} \right) \tag{11}$$

The k_m and n_m factor can be replaced and used in Equation (9).

The drilling fluid's effective viscosity can be obtained from Equation (12) (cP) [42]:

$$M_{eff} = PV + 300YP \frac{d_c}{V_{ann}} \tag{12}$$

where d_c is the cutting diameter (inch) and can be calculated by Equation (13) [40]:

$$d_c = 0.2 \cdot \frac{ROP}{RPM} \tag{13}$$

where RPM is the rotary speed of bit (rpm).

In Equation (13), based on [42,44], the maximum cutting diameter is 0.3–0.5 inch. Due to the use of directional drilling tools such as mud motors or the combination of a rotary steerable system (RSS) and a mud motor under a general name, which is referred to in the field as motorized RSS, due to the importance of considering the downhole RPM while drilling using the mud motor or the motorized RSS, Equation (13) was modified to Equation (14) to predict the modified average cutting diameter by including the specifications of the mud motor, such as the revolution per gallon ratio (x) and the GPM of the mud pump flow rate.

Thus, the modified cutting diameter can be obtained as follows:

$$d_{cm} = 0.2 \cdot \frac{ROP}{RPM + xGPM} \tag{14}$$

As was explained above, the CTR is calculated by dividing the transport velocity by the drilling fluid velocity. However, this method falls short because it overlooks a number of factors that affect the CTR, such as the cuttings density (Wc) and the low shear yield point ($LSYP$). Thus, from Equation (5), the ECD can be modified as follows based on PV and YP . Moreover, the Fann viscometer is a tool commonly utilized to measure shear stress readings at various rotational speeds, including 600 RPM, 300 RPM, 200 RPM, 100 RPM, 6 RPM, and 3 RPM. The PV and YP values can be calculated using Equations (15) and (16), with the shear stress readings obtained at 300 RPM and 600 RPM [7,42]:

$$PV_m = (R600 - LSYP) - (R300 - LSYP) \tag{15}$$

$$YP_m = (2R300 - LSYP) - (R600 - LSYP) \tag{16}$$

where $R600$ and $R300$ are the viscometer reading at 600 RPM and 300 RPM, respectively.

From Equations (5) and (12), the PV_m and YP_m can be replaced, and the following Equation (17) of ECD_m can be obtained:

$$ECD_m = MW_{eff} + \left(\left(\frac{0.085}{OH - OD_{pipe}} \right) \cdot \left((2R300 - LSYP) - (R600 - LSYP) + \frac{(R600 - LSYP) - (R300 - LSYP)V_{ann.m}}{300(OH - OD_{pipe})} \right) \right) \cdot 7.481 \tag{17}$$

In Equation (6), which represents the original annular mud velocity applied in the vertical hole section alone, V_{ann} is given as a function of GPM , OH , and OD . The modified annular velocity ($V_{ann.m}$), as defined in Equation (18), depends on the weight and flow

rate of the drilling fluid, the size of the drilled hole, the outer diameter of the drill pipe, the rate of penetration, the rotation of the drill string, the plastic viscosity, the yield point, the Fann viscometer readings at 3 and 6 rpm, the wellbore inclination, and the azimuthal directions [7,42].

$$\begin{aligned}
 &= \left(\frac{24.5 \cdot GPM}{OH^2 - OD_{pipe}^2} \cos(\alpha) \right) \\
 &+ \left(\frac{60}{(1 - (OD_{pipe})^2) * (0.64 + \frac{18.2}{ROP})} + \frac{ROP(OH^2)}{60(OH^2 - OD_{pipe}^2)} \right) \sin(\beta) \\
 &+ \frac{175(d_{cm}) \left(22 - \frac{MW_{eff}}{7.481} \right)^{2n_m}}{(MW_{eff} / 7.481)^{n_m} \cdot \left(\frac{2.4 \cdot V_{ann}}{OH - OD_{pipe}} \cdot \left(\frac{2n_m + 1}{3n_m} \right)^{n_m} \left(\frac{200Km(OH - OD_{pipe})}{V_{ann}} \right) \right)^{n_m}}
 \end{aligned} \tag{18}$$

where α is the open hole angle (degrees) and β is the open hole azimuth (degrees). Based on worldwide experience, while drilling, there is a recommended pump flow which can be applied while drilling [45]. Table 1 shows the recommended pump flow (GPM) based on the hole size diameters.

Table 1. The recommended GPM based on the hole size diameters.

Hole Size, inches	Recommended GPM, gal/min	V_{ann} , ft/hr
22	1000–1200	54–65
16	1000	108
12.5	950–1000	185–195
8.5	500–600	292–350
6.125	250–300	285–342
5 7/8	250–300	330–397

In Equation (8), V_{scm} represents the modified slip velocity of the cuttings (ft/min), which takes into account the influence of the mud weight and other factors. The slip velocity of the cuttings, along with the effect of the mud weight, is determined using Equation (19). This equation employs V_{s1} , V_{s2} , and V_{st} , which are cuttings velocities calculated based on the effective viscosity, the apparent viscosity, the rate of penetration, and the cutting in turbulent flow [40]. Moreover, the V_{sc} can be added to the equation to take into account the influence of the cutting rise and the average mud annular velocity to consider the hydraulic velocity influence. To calculate V_{s1} , V_{s2} , V_{st} , and V_{sc} Equation (19) can be utilized with the modified d_{cm} [46–48].

$$V_{scm} = \frac{V_{s1} + V_{s2} + V_{st} + V_{sc}}{4} \tag{19}$$

where

$$V_{s1} = 0.45 \left(\frac{Meff}{(MW_{eff} d_{cm})} \right) \left(\left(\frac{36800 MW_{eff} d_{cm}^3 (Wc - MW_{eff})}{Meff^2} \right) + 1 \right)^{0.5} - 1 \tag{20}$$

$$V_{s2} = \left(\frac{175(d_{cm})(Wc - MW_{eff})^{0.667}}{MW_{eff}^{0.333} Mapp^{0.333}} \right) \tag{21}$$

$$V_{st} = 113.4 \cdot \left(\frac{d_{cm}(pp - MW_{eff})}{CD \cdot MW_{eff}} \right) \tag{22}$$

where pp is the particle density (lb/cf), CD is the drag coefficient, which can be calculated using Equation (23), and Wc is the weight cutting (lb/cf), which can be calculated using Equation (24) as follows [36,49]:

$$CD = \frac{24}{Re} + (1 + Re)^{0.4} + e^{(1-Re)^{0.39}} \tag{23}$$

$$Wc = (MW_{eff}CCA + MW_{eff}) + (1 - CCA)MW_{eff} \tag{24}$$

where Re is the Reynolds number, which can be calculated using Equation (25) as follows [36,49]:

$$Re = \frac{2.4 \cdot MW_{eff} \cdot V_{ann.m} (OH - OD)}{\mu_{eff}} \tag{25}$$

where μ_{eff} is the effective viscosity (cP).

Equations (19)–(22) demonstrate that the average slip velocity is determined by averaging the values of the cuttings slip velocities under different flow regime types, each calculated using a respective equation. These equations also consider real-time drilling parameters, including the density of the cuttings, the drilling fluid weight, and the rheology of the drilling fluid. Moreover, based on [50], the original lifting capacity (LC) can be calculated by Equation (26) and can be modified to Equation (27), which can be considered as the ECD_m [50].

$$LC = \frac{MW}{Wc} \tag{26}$$

$$LC_m = \frac{ECD_m}{Wc} \tag{27}$$

Thus, the transport ratio in Equation (28) also accounts for these real-time drilling parameters (see Figure 4). Since these parameters significantly impact the actual transport ratio, the obtained Equation (28) modified transport ratio (CTR_m) is more precise than conventional Equation (2), which is used to calculate the transport ratio for the vertical tubes and is based on experimental work by Sifferman in 1974 [37].

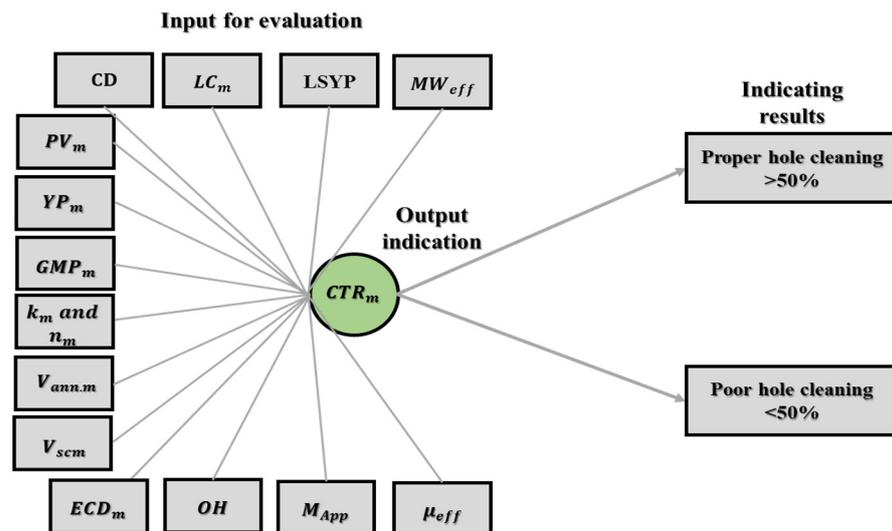


Figure 4. The input and output of the novel model CTR_m as a real-time evaluation for indicating the hole cleaning condition.

Equation (28) can be used to compute and finalize the modified CTR_m as a consequence:

$$CTR_m = \left(1 - \frac{V_{scm}}{V_{ann.m}LC}\right) 100 \tag{28}$$

Based on Figure 4, it is apparent that CTR_m can be calculated using the initial parameters CCA and MW_{eff} . Additionally, the model incorporates factors such as hydraulic velocities, the rheological properties of drilling fluids, flow regime, drag coefficient, cutting properties, equivalent circulating density, and lifting capacity to generate a novel CTR_m model. The novel CTR_m model serves as an indicator for the condition of hole cleaning and is evaluated using two criteria. If the CTR_m is greater than 50%, this indicates proper hole cleaning. Conversely, a CTR_m value less than 50% signifies poor hole cleaning.

4. Field Applications Using the Novel Cutting Transport Ratio

The effectiveness of the novel CTR_m was confirmed during the directional drilling of the 12.25" intermediate sections of two offshore wells, which were Well-A and Wells-B (see Figure 5a,b), and onshore Well-C with a 12"-diameter hole section (see Figure 6a), as well as a 8.5" hole section drilled horizontally (see Figure 6b). These directional drilling sections were highly deviated, with the first two starting at 30 degrees and the third approaching a near-horizontal inclination of 90 degrees at the top of the reservoir in Well-A and Well-B.

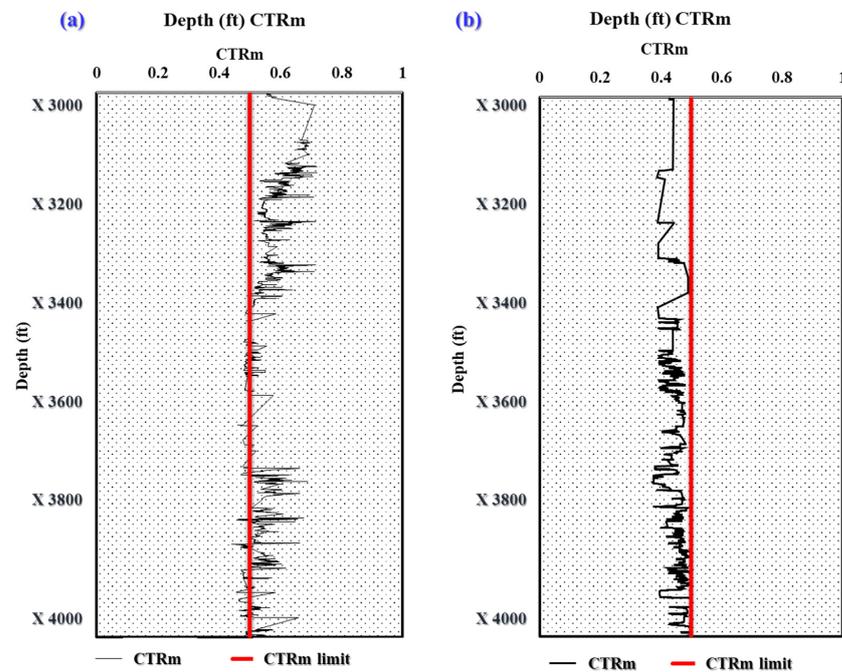


Figure 5. Application of CTR_m in the offshore proper hole cleaning of Well-A (a) and the poor hole cleaning of Well-B (b).

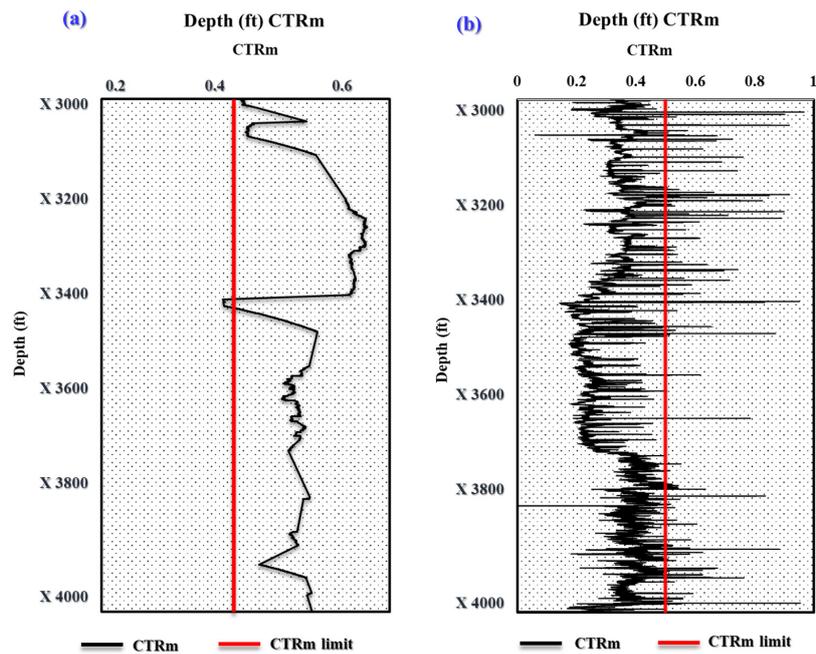


Figure 6. Application of CTR_m in the offshore gas vertical Well-C (a) and the horizontal Well-B (b).

Table 2 provides an overview of the essential characteristics of the drilled formations and the cuttings generated during the drilling of these sections. An oil-based drilling fluid was used to drill the two sections, and Table 3 summarizes the drilling fluid properties employed in these sections of Well-A and Well-B. Appendix A shows the input, calculated, and output parameters, and Appendix B shows the methodology of the novel model CTR_m.

Table 2. Formation and drilling cuttings’ properties.

Parameter	Value
Formation lithology type	Sandstone, limestone, and shale
Formation temperature	(140–155) °F
Formation porosity	0.15–0.25
Washout	10–30%
Density of drill cuttings	(20–24) (ppg)
Size of drill cuttings	(0.2–0.375) (inches)

Table 3. The drilling fluid characteristics.

Parameter	Characteristic Range
Oil-based drilling mud density	80 lb/ft ³
Oil ratio	(0.75–0.8)
Water ratio	(0.2–0.25)
Electrical stability	(400–600) volts
Low-gravity solids	(2.5–5) (%)
High-gravity solids	(10–15) (%)
March funnel viscosity	(65–75) (s)
Solid content	(15) (%)
Mud solid control equipment efficiency	0.5

4.1. Application of CTR_m in Offshore Well-A and Well-B

The effectiveness of the developed CTR_m model was evaluated in two wells with proper and poor hole cleaning, and its performance was tested and verified in the actual drilling site. The integration of the CTR_m model and its automation has proven to be a

beneficial tool in drilling operations, as it helps to prevent issues that may arise from inadequate hole cleaning. The following subsection describes the outcomes of implementing the CTR_m model in Well-A and Well-B (see Figure 5). As seen in Figure 5a, a case involving Well-A, CTR_m was utilized during drilling to optimize the ROP. At a depth of X3000 ft, the CTR_m value was above 0.7, which suggests that the wellbore was clean and free from any cutting accumulation. The drilling crew did not notice any other indications of cuttings' build-up. However, when the drilling reached a depth of X3800 ft, the CTR_m value began to steadily decrease from 0.7 until it eventually dropped to less than 0.5 at X3891 ft. On the other hand, as seen in Figure 5b, the second well studied in this research is referred to as offshore Well-B, where CTR_m was utilized to evaluate the performance of hole cleaning in relation to cuttings' accumulation and to show the performance of ROP.

Table 4 presents a summary of the impact of implementing CTR_m on well performance, with a particular focus on the enhanced hole cleaning achieved in Well-A. The results showed that the average CTR_m value of over 0.64 resulted in a significant improvement in the ROP in Well-A, which reached 205 ft/hr, compared to the 70 ft/hr of ROP observed in Well-B. These results demonstrate that the successful achievement of proper hole cleaning can lead to a substantial improvement in well performance.

Table 4. Impact of employing CTR_m .

Performance of Well-A Employing CTR_m					
Items	Output	Minimum	Maximum	Average	Remark
1	CTR_m	0.49	0.79	0.64	Effective hole cleaning
2	ROP	120	280	205	Improved the drilling performance due to optimized efficiency of hole cleaning
Performance of Well-B Employing CTR_m					
Items	Output	Minimum	Maximum	Average	Remark
1	CTR_m	0.39	0.49	0.44	Improper removal of cuttings from the wellbore
2	ROP	105	264	135	Decreased drilling efficiency and performance attributable to inefficient wellbore cleaning

The overall analysis of the results in Table 4 reveals that the average ROP improvement in Well-A can be attributed to the effective hole cleaning achieved through the implementation of CTR_m . However, there were some instances where the CTR_m values fell below the limit of 0.5, specifically from depth X3000 to X4000 ft, due to poor hole cleaning. This led to cuttings' accumulation in the wellbore and decreased the ROP to 105 ft/hr. In other words, the drilling process failed to effectively remove the cuttings, which impeded the drilling progress and resulted in a slower-than-expected ROP. These findings underscore the importance of maintaining proper hole cleaning throughout the drilling process to ensure optimal well performance.

4.2. Application of CTR_m in Offshore Well-C and Well-D

In Figure 6a, a case involving Well-C which was a vertical gas well, CTR_m was utilized during drilling to optimize the ROP. At a depth of 3250ft, the CTR_m value was above 0.6, which suggests that the wellbore was approximately clean and free from cutting accumulation. The drilling crew did not notice any other indications of cutting accumulation or issues such as stuck pipes. However, when the drilling reached a depth of X3423 ft, the CTR_m value began to steadily decrease from 0.6 until it eventually dropped to less than 0.5 at X3439 ft due to the fact that there had been some complications during the drilling process in formation, which can affect the ability to remove cuttings effectively, leading to a sudden decrease in hole cleaning efficiency. On the other hand, as shown in Figure 6b, Well-D was a horizontal well that was the subject of a particular case. Moreover, the average

of the CTR_m was 0.45, which indicated inefficient hole cleaning, due to the stuck pipe, which can be noticed at depth X3850–X400 ft (see Figure 6b).

Generally, poor wellbore cleaning can result in the accumulation of cuttings and other debris in the wellbore, leading to reduced drilling efficiency and an increased risk of complications. Similarly, stuck pipe incidents can significantly impede drilling progress and result in costly downtime. By addressing these issues promptly and effectively, drilling operations can maintain optimal performance and avoid potential delays and complications. Employing efficient wellbore cleaning techniques such as the novel CTR_m model can help improve drilling efficiency and prevent issues related to stuck pipes. It is essential to continuously monitor and evaluate drilling operations to identify potential issues and take proactive steps to address them in a timely manner.

Table 5 provides a summary of the impact of implementing CTR_m on well performance, particularly in relation to the enhanced hole cleaning achieved in the vertical gas well, Well-C. The average CTR_m value in Well-C was over 0.57, and the average ROP was 14.3 ft/hr. These results demonstrate the positive impact of effective wellbore cleaning and the successful implementation of the CTR_m model on drilling performance. In contrast, the average CTR_m value in the horizontal well, Well-D, was 0.45, which is below the limited value due to stuck pipe issues. The average ROP in Well-D was 93.4 ft/hr, which was also affected by inefficient wellbore cleaning and stuck pipe incidents. These results highlight the importance of identifying and addressing issues related to wellbore cleaning and stuck pipe promptly to maintain optimal drilling performance and prevent costly downtime.

Table 5. Impact of employing CTR_m on well performance.

Performance of Well-C Employing CTR_m					
Items	Output	Minimum	Maximum	Average	Remark
1	CTR_m	0.48	0.63	0.57	Proper removal of cuttings from the wellbore
2	ROP	5.0	25.7	14.3	Normal drilling efficiency and performance due to proper wellbore cleaning
Performance of Well-D Employing CTR_m					
Items	Output	Minimum	Maximum	Average	Remark
1	CTR_m	0.58	0.95	0.45	Poor removal of cuttings from the wellbore
2	ROP	0.552	267	93.4	Decreased drilling efficiency and performance attributable to inefficient wellbore cleaning and stuck pipes

Based on the results above, in Well-A, the novel CTR_m model improved the rate of penetration by 52% compared to Well-B. These results indicate that the model is an effective solution for enhancing drilling performance, identifying complications, and improving hole cleaning efficiency. Real-time evaluations showed that the model could identify hole cleaning efficiency during normal drilling operations in Well-C, and detect stuck pipe issues in Well-D. Overall, the novel CTR_m model has proven to be a valuable tool for optimizing drilling operations and addressing potential issues in real-time.

5. Conclusions

The novel CTR_m model takes into account various real-time drilling parameters to evaluate and optimize drilling performance. By utilizing these parameters, the model can provide accurate assessments of hole cleaning efficiency, identify potential issues in real-time, and help to prevent complications such as stuck pipe incidents. The real-time drilling parameters that the CTR_m model accounts for may include the drilling fluid flow rate, pump pressure, and drill string rotation speed, among others. By incorporating these parameters into its calculations, the CTR_m model provides a comprehensive and reliable assessment of drilling performance, which can help to optimize drilling operations and enhance overall efficiency. The following points can be summarized:

1. The CTR_m , a crucial hole cleaning indicator, is monitored in real-time using drilling factors such as cuttings features, drilling mechanical parameters, well trajectory profiles (the well path, which contains the inclinations and the azimuths), and fluid rheological properties, with consideration of the LSYP as it is a signal for hole cleaning effectiveness in directional drilling, along with calculated cuttings slip and annular velocities. This monitoring helps engineers identify well cleaning and ROP issues, leading to improved efficiency through fluid optimization, drilling adjustments, and advanced technology use. The novel CTR_m model, instead of commercial software, facilitates real-time optimization and interventions, accounting for wellbore shape changes and spontaneous field data. Connecting CTR_m to the driller's control panel enables immediate evaluation and remedial actions for hole cleaning.

2. The novel CTR_m was tested and validated in the field. The obtained results proved that the efficiency of the drilling wells was enhanced. Drilling practices might be greatly improved by utilizing the novel CTR_m and its automation, which would reduce any possible issues brought on by insufficient hole cleaning.

3. Real-time evaluation demonstrated that the model could identify hole cleaning efficiency during normal drilling operations in Well-C and detected stuck pipe issues in Well-D. Furthermore, in comparison to Well-B, the novel CTR_m model improved the rate of penetration by 52% in Well-A. Overall, the results indicate that the novel CTR_m model is an effective solution for enhancing drilling performance, identifying complications, and improving hole cleaning efficiency.

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Nomenclature

AV or V_a	annular velocity, ft/min
V_{ann}	annular velocity, ft/min
M_{App}	apparent viscosity, cP
CCI	carrying capacity index
CCA	concentration of cuttings in the annulus
K	consistency factor, cP
d_{cm}	cutting diameter, inch
V_{Cr}	cutting rise velocity, ft/min
V_{sc}	cutting slip velocity, ft/min
CTR	cutting transport ratio
R3	dial reading at 3 revolutions per minutes, cP
R300	dial reading at 300 revolutions per minutes, cP
R6	dial reading at 6 revolutions per minutes, cP
R600	dial reading at 600 revolutions per minutes, cP
V_s	downward velocity, ft/min
CD	drag coefficient
MW_{eff}	effective mud weight, pcf
μ_{eff}	effective viscosity, cP
ECD	equivalent circulating density, pcf
ERD	extended reach drilling
n	flow behavior index
OH	hole diameter, inch
MCDs	mechanical hole cleaning devices
$V_{ann \cdot m}$	modified annular velocity, ft/min
k_m	modified consistency factor, cP
ECD _m	modified equivalent circulating density, pcf
n_m	modified flow behavior index
LC _m	modified original lifting capacity
PV _m	modified plastic viscosity, cP
V_{scm}	modified slip velocity of the cuttings, ft/min
YP _m	modified yield point, cP
MW	mud weight, pcf
CTR _m	novel model transport ratio, % or fraction
α	open hole angle, degrees
β	open hole azimuth, degrees
LC	original lifting capacity
OD	outer diameter of drill pipe, inch
pp or W_c	particle density or weigh of the cuttings, lb/cf
PV	plastic viscosity, cP
GPM	pump flow rate, Gal/min
ROP	rate of penetration, ft/hr
x	revolution per gallon ratio
RPM	revolution per minute, rev/min
Re	Reynolds number
RSS	rotary steerable system
V_C	upward velocity of the cuttings, ft/mins
V_{s1} and V_{s2}	velocity based on effective viscosity, apparent viscosity, and the weight and diameter of cuttings, ft/min
V_{st}	velocity based on the cutting in turbulent flow, ft/min
WOB	weight on bit, Klb
YP	yield point, cP

Appendix A. The Measured, Calculated, and Output Parameters for the Novel Model CTR_m

Table A1. The input, calculated, and output parameters for the novel model CTR_m.

Input	Calculated Parameters	Output
MW	CCA	
PV	MW _{eff}	
YP	W _C	
R600	V _{ann}	
R300	V _{Cr}	
R3	V _{sc}	
R6	V _{ann·m}	
RPM	V _{s1}	
GPM	V _{s2}	
ROP	V _{st}	CTR _m
OH	V _{scm}	
OD	CD	
α	Re	
x	LC	
	LC _m	
	dc _m	
	M _{App}	
β	PV _m	
	YP _m	
	ECD _m	

Appendix B. The Methodology of the Novel Model CTR_m

The flow chart presented below demonstrates how the CTR_m can be calculated using the initial parameters CCA and MW_{eff}. In addition to these parameters, the novel CTR_m model takes into account other various factors such as hydraulic velocities, the rheological properties of the drilling fluids, the flow regime, the drag coefficient, the cuttings properties, the equivalent circulating density, and the lifting capacity.

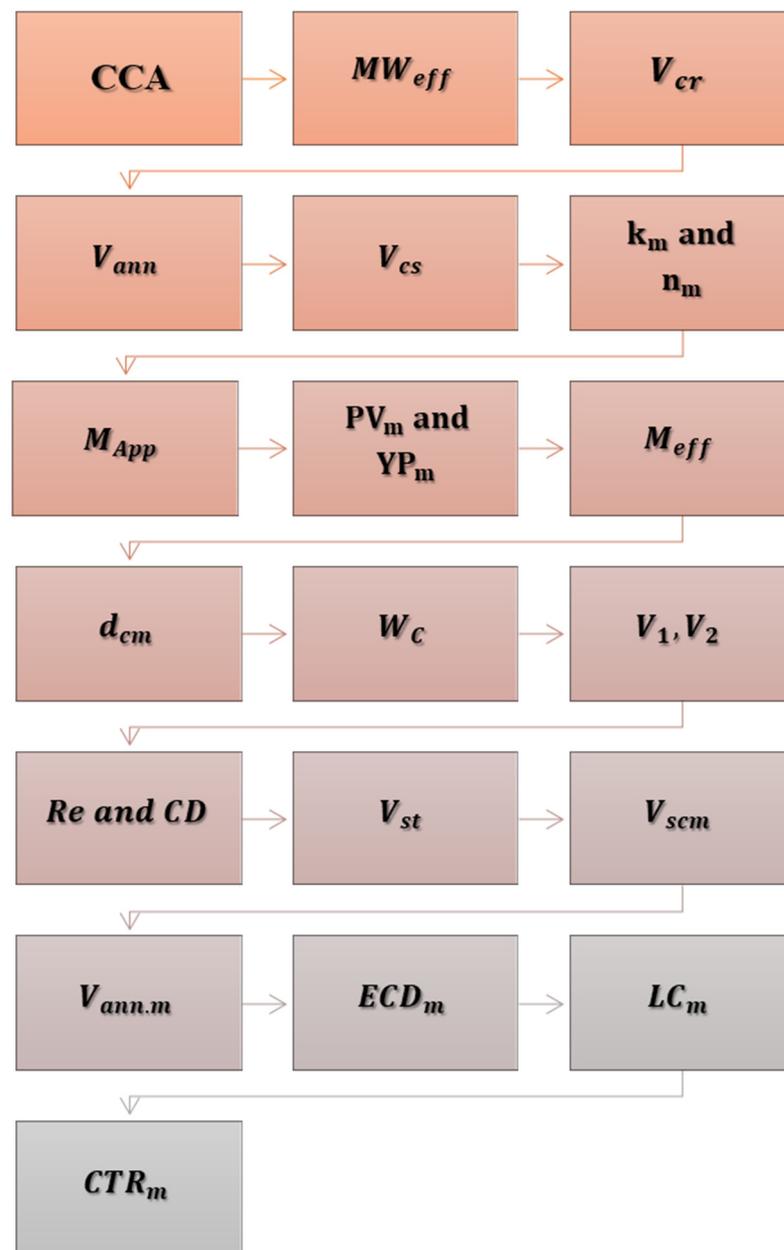


Figure A1. The Methodology of the Novel Model CTR_m .

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