Journal of Petroleum Science and Engineering 221 (2023) 111254

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Analysis of cuttings concentration experimental data using exploratory data analysis

Dipankar Chowdhury [a,*], Sigve Hovda [a], Bjørnar Lund [b]

[a] *Department of Geoscience and Petroleum, Norwegian University of Science and Technology, 7034, Trondheim, Norway*
[b] *Department of Petroleum, SINTEF, 7031, Trondheim, Norway*

ARTICLE INFO

Keywords:
Experimental hole cleaning data
Downhole cuttings concentration
Exploratory data analysis
6D scatter plot
Kendall’sτ

ABSTRACT

Cuttings transportation is a complex phenomenon involving many inter-acting variables. Experimental investigations on cuttings transport are carried out by different research groups for decades and varying findings are reported which points out to the need for a methodical data analysis approach. In the current paper, six experimental datasets (702 observations) are analyzed using exploratory data analysis (EDA) in a two-fold manner – univariate and multivariate analysis. Univariate analysis shows the asymmetry in distribution for each experimental parameter indicating the need for a nonparametric modeling approach. Multivariate analysis shows the interaction of the experimental parameters among themselves and their influence on downhole cuttings concentration (Cc) using 6D scatter plots and correlation coefficients (Kendall’s τ). EDA of the current experimental data reveals the following major findings:

- Smaller Cc in concentric vertical wells compared to concentric non-vertical wells.
- Drilling fluid flow rate is a dominant operational parameter in vertical wellbore cleaning while string rotation (RPM) is dominant in non-vertical wellbore cleaning.
- Little impact of RPM in concentric vertical well and negative eccentric deviated/highly deviated well cleaning. However, RPM together with drilling fluid flow rate provides better cleaning of non-vertical wells with positive eccentricity.
- RPM has higher influence on cuttings transport in narrow annulus compared to that in wide annulus.
- Assuming drilling fluid of sufficient viscosity and drill string rotation present, low viscous fluid under turbulent flow and high viscous fluid under laminar flow provide better hole cleaning. Further, Kendall’s τ indicates apparent viscosity playing a more significant role in cleaning deviated wellbores compared to other inclinations for the current dataset.
- Drilling fluid flow rate influences the transport of heavier cuttings and larger cuttings more while RPM has higher influence on the transport of lighter cuttings and smaller cuttings.
- Better hole cleaning by heavier drilling fluids than that by lighter fluids.

1. Introduction

Mechanical wellbore instability (also termed as ‘stuck pipe’ or ‘tight hole’ by drillers) in overburden and in reservoir is associated with poor hole cleaning and can cost 5–10% of drilling costs in exploration and production (Fjar et al., 2008). Inadequate borehole cleaning can cause premature bit wear, excessive torque and drag during drilling, pack-off, reduced drilling rate or rate of penetration (ROP), drillpipe failure, mud contamination, trouble during logging and casing/liner cementing and excessive equivalent circulating density (ECD) leading to formation breakdown (Deshmukh and Dewangan, 2022; Rabia, 1989). Badrouchi (2021) has estimated poor hole cleaning can cause an increase in ECD of more than 0.1 sg. He, therefore, has recommended considering downhole cuttings concentration during well planning to estimate a realistic

---

* Corresponding author.
E-mail address: dipankar.chowdhury@ntnu.no (D. Chowdhury).

https://doi.org/10.1016/j.petrol.2022.111254
Received 29 July 2022; Received in revised form 16 October 2022; Accepted 12 November 2022

value of ECD during drilling and thereby avoiding non-productive time (NPT) due to poor hole cleaning. This is in line with the recommendation of Xiang (Xiang et al., 2012).

Cuttings transport and hence borehole cleaning is a complex phenomenon as it involves multiphase flow (Deshmukh and Dewangan, 2022) and interactions between different drilling parameters such as drillpipe eccentricity, drilling fluid flow rate and rheology, cuttings size and density, ROP and drillstring rotation. To understand the cuttings transport process together with the influence of different drilling parameters on cuttings transport, different research groups have conducted experimental investigations for decades. Analysis of the experimental data is of utmost importance to get insight into the complex cuttings transport process and understand the influence of the different drilling parameters on cuttings transport (Deshmukh and Dewangan, 2022).

Exploratory data analysis (EDA) is an area of statistics and data analysis where a set of data is explored using descriptive statistics and visualization techniques without making any assumption (Martinez et al., 2017). It aims at revealing patterns and features in data to enable the analyst better understand, analyze and model the data (Martinez and Martinez, 2001). EDA is applied in different disciplines for data analysis. Kurzl has applied EDA to analyze geochemical data derived from a regional stream sediment survey in Austria (Kürzl, 1988). Jansen and Kelkar have used EDA to analyze production data to find out inter-well communication (Jansen and Kelkar, 1996). Vieira et al. have used EDA to find out the origin of crude oil in the Espírito Santo sedimentary basin located on the southeastern Brazilian coast. Flumignan et al. have showed the application of EDA to determine whether the gasoline quality from automobiles in Brazil is in compliance with the specifications set by the government (Flumignan et al., 2007). Kumar et al. have performed an extensive analysis of the data collected by their soil sensors through EDA to develop an expert system for predicting different fungal diseases of plants (Kumar et al., 2020). Ogunsina et al. have applied EDA to analyze historical airline scheduling and operations data to find out causes for airline schedule disruptions (Ogunsina et al., 2021).

This paper presents EDA of cuttings concentration (Cc) experimental data where experiments are performed by different research groups using different test facilities. The experiments are conducted using different test setup and using different test fluids. They are also conducted at different geographical locations. Data processing and outlier removal procedure followed for the collected experimental dataset are also discussed in this paper. The EDA of the processed data is conducted in a two-fold manner – univariate and multivariate analysis. In addition to EDA, a literature survey is presented with a focus of finding out the influence of different drilling parameters on downhole cuttings concentration as found by different researchers.

This paper is arranged as follows – section 2 presents a literature survey on the different drilling parameters affecting downhole cuttings concentration, section 3 talks about the different experimental data used in the current work, section 4 presents data processing and outlier removal procedure followed in the current work, section 5 presents EDA of the processed experimental dataset and finally concluding remarks are made in section 6.

2. Literature survey

Cuttings transport through a wellbore is studied experimentally for decades. The following drilling parameters are reported to affect cuttings transport (and thereby downhole cuttings concentration) from laboratory experiments/studies:

2.1. Annulus size

Annulus size is the diametrical difference between drill pipe (DP) size and hole or casing size. Rabia (1989), Campos (1995), Ahmed et al. (2010), Gavignet and Sobey (1989) and Badrouchi (2021) have reported the influence of annulus size on cuttings transport. An increase in DP size for a given hole/casing size and flow rate, increases drilling fluid annular velocity (= flow rate/annular cross-sectional area perpendicular to flow) and hence reduces the critical drilling fluid flow rate needed for efficient hole cleaning. Based on a two-layer model, Gavignet and Sobey have recommended using as large DP as possible to drill highly deviated wells. Their model predicts lower critical drilling fluid flow rate with bigger OD DP for the same hole size. Ahmed et al. have also observed lower cuttings concentration with larger OD DP during their experiments with different annulus sizes. However, Badrouchi has pointed out that an increase in DP size and thereby reduction in annulus size leads to higher annular frictional pressure drop during circulation. So, a reduction in annulus size can improve hole cleaning but at the risk of increased ECD. DP size hence needs to be chosen such that it optimizes hole cleaning without ECD exceeding the formation strength and thereby leading to a lost circulation event. However, Rabia has considered the effect of annulus size on cuttings transport minor.

2.2. Cuttings size and density

Rabia (1989), Sifferman and Becker (1992), Campos (1995), Larsen et al. (1997), Azar and Sanchez (1997), Duan et al. (2006), Li et al. (2004), Bilgesu et al. (2007), Li and Luft (2014a), Cayeux et al. (2014), Zhang (2015), Reda et al. (2018), Huque et al., 2020a, 2022, Deshmukh and Dewangen (Deshmukh and Dewangan, 2022) and Abbas et al. (2022) have studied the effect of cuttings size on hole cleaning. Rabia and, Sifferman and Becker have considered cuttings size influence on hole cleaning as moderate while Li and Luft have reported it minor for the cuttings sizes [0.15, 7] mm. Larsen et al. have observed reduced critical transport velocity for larger cuttings compared to smaller cuttings to prevent the formation of cuttings bed. Li et al. have reported faster growth rate of cuttings bed height in a horizontal well for cuttings smaller than 5 mm using their 1D transient mechanistic model. Cayeux et al. have also observed faster cuttings bed growth with smaller cuttings compared to that with bigger cuttings using their transient cuttings transport model applied to a North Sea designer well with 65° inclination for the cuttings sizes in the range (Deshmukh and Dewangan, 2022; Martinez et al., 2017) mm. Abbas et al. have experimentally observed easier transport of larger cuttings using water-based test fluids (Herschel-Bulkley) for a simulated horizontal well. However, Rabia has pointed out that fist-size or larger cuttings need to be broken into small cuttings mechanically before they can be transported out of the wellbore. Li and Luft have also pointed out that transportation of cuttings larger than 10 mm is difficult in all inclinations. Deshmukh and Dewangen have reported that hard formations, like clay and limestone, produce large cuttings while soft formations, like sandstone and siltstone, produce small cuttings. They have further reported that cuttings produced from soft formations are more rounded in shape and mostly get dissolved in drilling fluid. Reda et al. have pointed out that cuttings shape and size are related to the bit used during drilling. They have further commented that cuttings shape and size are non-controllable parameters due to cuttings grinding and breakage by drill string rotation during drilling operation.

Bilgesu et al., through CFD simulation performed assuming steady state condition and concentric annulus, have shown more efficient hole cleaning for large cuttings (8 mm) than small cuttings (3 mm) for horizontal and highly deviated (60° and 75°) wellbores due to greater drag force than gravitational force acting on the large cuttings. Zhang has also reported the same as Bilgesu et al. Zhang has further pointed out that small cuttings are transported most efficiently at all inclinations by using low viscosity fluid while large cuttings are transported most efficiently with high viscosity fluid between 0° – 50° inclination. Small cuttings tend to accumulate more in a horizontal well section than in a highly deviated well section. Large cuttings, on the other hand, show opposite behavior. Bilgesu et al. have also observed greater effect of drillpipe rotation on the transport of small cuttings than that of large cuttings using their developed CFD model. Duan et al. have reported that RPM together with drilling fluid rheology plays a key role in small cuttings transport in a horizontal well. Huque et al., through CFD simulation, have observed that cuttings between 1 mm and 2 mm in a horizontal wellbore are challenging to remove while smaller cuttings (≤0.5 mm) are carried along with the drilling fluid out of the horizontal wellbore as suspended particles if the fluid has sufficient viscosity. They have further reported that an increase in drilling fluid flow rate is more effective for larger cuttings compared to the smaller ones for hole cleaning.

In a particular experiment, cuttings density is typically kept constant. According to Azar and Sanchez, the typical density of cuttings is 2.6 sg. Intuitively, a heavier cuttings particle is difficult to lift and transport out of the well compared to a lighter one (assuming all other parameters are kept constant). Reda et al. have found the same from their parametric study using a developed statistical model. They have shown that the higher the cuttings density the poorer is the cuttings transport efficiency.

2.3. Drilling fluid flow rate

Iyoho (1980), Tomren et al. (1986), Okrajni and Azar (1986), Rabia (1989), Becker et al. (1991), Campos (1995), Azar and Sanchez (1997), Li and Walker (1999), Adari et al. (2000), Li et al. (2004), Mitchel and Ravi (Mitchell, 2006), Li et al. (2004), Bilgesu (Bilgesu et al., 2007), Ahmed et al. (2010), Nazari et al. (2010), Ogurinde and Dosunmu (Ogunrinde and Dosunmu, 2012), Li and Luft (2014a), Zhang (2015), Benjamin (Werner, 2018), Sayindla (2018), Reda et al. (2018), Huque et al., 2020a, 2022, Deshmukh and Dewangen (Deshmukh and Dewangan, 2022) and, Rasool and Aadnøy (Rasool Khosravanian, 2022) have reported drilling fluid flow rate to be one of the major drilling parameters affecting cuttings transport during drilling. Azar and Sanchez have identified drilling fluid flow rate dominant over all other drilling parameters for cuttings transportation. Ahmed et al. have statistically found the same for their experimental setup. Mitchel and Ravi have pointed out that sufficient flow rate will always remove cutting irrespective of fluid rheology, hole size and inclination. However, maximum applicable flow rate during drilling is limited by pump capacity and/or maximum allowable ECD based on formation strength. Keeping all other parameters constant, it is typically observed that the higher the flow rate the lower the cuttings concentration.

Sayindla has found flow rate having a greater positive impact on cuttings transport for less viscous mud compared to more viscous mud. Iyoho and Adari et al. have observed turbulent flow providing better hole cleaning over laminar flow. Ogurinde and Dosunmu have suggested turbulent flow for preventing cuttings bed development. Pilehvari et al. have also recommended turbulent flow for inclined/horizontal wellbore sections if it is practically possible without exceeding the formation strength limit (Pilehvari et al., 1999). If turbulent flow is not possible to achieve in a large horizontal wellbore, Pilehvari et al. have recommended using viscous drilling fluid with high suspension properties and high dial readings at low shear rates. Becker et al. have observed laminar flow for inclination ≤45° and turbulent flow for inclination >60° efficient for cuttings removal. Making similar observations as Becker et al., Deshmukh and Dewangen have further reported that both laminar and turbulent flow have the same effect on cuttings removal for the intermediate inclination range in between 45° and 55°. Rabia has pointed out to the conflicting requirements of laminar flow for hole stability and turbulent flow for hole cleaning. He has further commented that these conflicting requirements can be resolved by maintaining laminar flow in the wellbore annulus, but with a much flatter drilling fluid velocity profile attained through maintaining the corresponding flow behaviour index (n) to a value less than 1.

2.4. Drilling fluid density

Rabia (1989), Bourgoyne et al. (1986), Sifferman and Becker (1992), Campos (1995), Larsen et al. (1997), Azar and Sanchez (1997), Li et al. (2004), Li and Luft (2014a), Reda et al. (2018) and Abbas et al. (2022) have pointed out the influence of drilling fluid density on cuttings removal from a wellbore. Sifferman and Becker, Azar and Sanchez, Larsen et al. and Abbas et al. have observed that an increase in drilling fluid density results in a reduction in cuttings concentration. According to Qahtani and Amanullah (2010), Reda et al. and Abbas et al., an increase in drilling fluid density provides higher buoyancy force for cuttings (assuming unchanged cuttings density) and hence its easier removal from the wellbore. However, Bourgoyne et al., Azar and Sanchez and, Li and Luft have pointed out that increasing drilling fluid density decreases ROP and thereby causes a financial penalty. Rabia has considered the effect of drilling fluid weight on cuttings transport moderate. On the other hand, Li et al. have found the impact of drilling fluid density on cuttings bed height in a horizontal well insignificant through sensitivity analysis of their developed 1D transient mechanistic model. Rabia, based on experimental observations, has pointed out that the drilling fluid density effect on hole cleaning is most pronounced at low range of annular drilling fluid velocities (0.3–0.6 m/s).

2.5. Drilling fluid rheology

Iyoho (1980), Tomren et al. (1986), Okrajni and Azar (1986), Rabia (1989), Becker et al. (1991), Rabia (1989), Sifferman and Becker (1992), Azar and Sanchez (1997), Larsen et al. (1997), Li and Walker (1999), Adari et al. (2000), Li et al. (2004), Duan et al. (2006), Yu et al. (2007), Ozbayoglu et al. (2008), Qahtani and Amanullah (2010), Sorgun (2010), Li and Luft (2014a), Zhang (2015), Ytrehus (Ytrehus et al., 2020, 2021a), Benjamin (Werner, 2018), Sayindla (2018), Alkinani et al. (2019), Al-Rubaii et al. (2020), Huque et al., 2020a, 2020b, 2022, and Deshmukh and Dewangen (Deshmukh and Dewangan, 2022) have studied the effect of different drilling fluid rheological properties (viscosity, rheological constants such as flow behavior index (n) and consistency index (K), plastic viscosity (PV), yield point (YP), YP/PV or thickening ratio) on cuttings transport in deviated wells.

Iyoho, Tomren et al., Rabia and Yu et al. have identified drilling fluid rheological properties as one of the major parameters affecting cuttings transport in deviated wells. However, Okrajni and Azar, and Becker et al. have reported no effect of drilling fluid rheological properties on cuttings transport under turbulent flow, while they have reported better hole cleaning provided by drilling fluid with high rheological properties at laminar flow for low inclination wells ($\Theta < 45^\circ$). Li and Walker have found that a low viscosity fluid in turbulent flow for horizontal/near-horizontal holes and a high viscosity fluid in laminar flow for vertical/near-vertical holes provides the best hole cleaning. Li et al. have recommended the use of a thin or low viscous drilling fluid if sufficient pump capacity is available due to low ECD associated with a thin drilling fluid compared to that of a thick or highly viscous drilling fluid. This is in line with the observation of Azar and Sanchez who have observed high viscosity fluid providing poor hole cleaning due to higher hydraulic requirement compared to that of a less viscous fluid in directional wells. Pointing out fluid rheology as a controllable field parameter influencing cuttings transport strongly, Adari et al. have reported that either a low viscous fluid at a high flow rate or a very high viscous fluid at a high flow rate provides optimum hole cleaning in a horizontal fully eccentric well in absence of drillstring rotation. Huque et al. have also observed high viscous drilling fluid providing better hole cleaning in horizontal and near-horizontal wellbores. Deshmukh and Dewangen have reported that increase in effective viscosity in vertical wells provides better hole cleaning due to increase in drilling fluid's cuttings carrying capacity. However, this increase in effective viscosity leads to formation of cuttings bed in deviated and horizontal wellbores due to not attaining the turbulent flow conditions. Rabia has expressed an opinion that a low viscous mud in turbulent flow performs as good as a high viscous mud in laminar flow.

Ytrehus et al. have verified the field observation that low viscous oil-based muds (OBM), when drillstring rotation is not used, are more efficient than high viscous OBMs for deviated and horizontal wellbores through experiments. The cuttings transport efficiency of high viscous OBMs improves significantly with the use of high drillstring rotation. Based on the observations, Ytrehus et al. have suggested using low viscous OBM with high flow rates when the ECD window is narrow while high viscous OBM with drillstring rotation when the ECD window is wide. Ytrehus et al. have further reported that OBM provides better hole cleaning than water-based mud (WBM) of similar viscosity for horizontal and deviated wellbores (90° and 60°) with and without drillstring rotation, while the opposite is observed for less deviated wellbore (48°) without drillstring rotation. For the 48° inclination, it is further observed that the hole cleaning performance of OBM improves significantly with drillstring rotation. In contrary to the observation of Ytrehus et al., Al-Rubaii et al. have reported that hole cleaning is harder with OBM than with WBM due to cuttings not being disbanded into OBM and, OBM being more Newtonian and less thixotropic than WBM. Sifferman and Becker have reported cuttings bed slides more in OBM compared to WBM.

Benjamin has reported that viscoelastic properties (such as yield stress and linear viscoelastic range) have little impact on cuttings transport. However, the viscoelastic properties are observed to have more influence on the resistance of cuttings bed to erosion. Sayindla has found that flow rate has a greater positive impact on cuttings transport for less viscous mud compared to more viscous mud. Ozbayoglu et al. have reported that the contribution of RPM to hole cleaning increases with an increase in fluid viscosity compared to the non-rotating case. Rabia and, Deshmukh and Dewangen have reported that fluids with low flow behaviour index (n) provide better hole cleaning as the fluid velocity near the wall is higher (flat velocity profile instead of the parabolic velocity profile associated with high values of n).

Alkinani et al. using Pearson correlation, a widely used statistical measure of linear relationship between two variables, have reported a high linear relationship between YP and flow rate while a statistically insignificant linear relationship between PV and flow rate. They have suggested an increase of the thickening ratio (YP/PV) to maximize hole cleaning. This can be achieved by increasing drilling fluid flow rate.

Saasen (1998), advocating sufficiently large frictional pressure loss in the annulus as the major contributor for proper hole cleaning in deviated well irrespective of drilling fluid design, has pointed out that viscosity, as measured by standard methods, is not a major parameter affecting hole cleaning. Saasen has pointed out that RPM will remove more cuttings from a cuttings bed formed in a WBM than that is formed in an OBM due to the gel structure formed by the polymers typically present in a WBM. The lower the polymer content of a WBM, the lower the impact of RPM on the cuttings bed. However, it is to be noted that polymeric consolidation of the bed is to be avoided if extensive drillstring rotation is needed for removing cuttings from the bed.

Mitchel and Ravi (Mitchell, 2006) have highlighted that the typical field practice of increasing either flow rate or mud viscosity upon encountering inefficient hole cleaning can lead to reduced ROP.

2.6. Eccentricity

Iyoho (1980), Tomren et al. (1986), Peden et al. (1990), Rabia (1989), Sifferman and Becker (1992), Campos (1995), Azar and Sanchez (1997), Li et al. (2004), Zhang (2015), Sayindla (2018), Deshmukh and Dewangen (Deshmukh and Dewangan, 2022) and Abbas et al. (2022) have evaluated eccentricity as one of the drilling parameters affecting cuttings transportation. Rabia has considered the impact of eccentricity on hole cleaning minor while Sifferman and Becker have reported it moderate. Li et al. have reported an insignificant effect of hole eccentricity on cuttings transport in a horizontal well through sensitivity analysis of a developed one-dimensional transient mechanistic model.

Both Iyoho and Tomren et al. have reported positive eccentricity at inclinations larger than 55° and negative eccentricity for inclinations less than 35° to be the worst scenario for cuttings transportation. In the transition zone between 35° and 55°, the effect of eccentricity on cuttings transport is inconsistent. Zhang has made similar remarks as Iyoho and Tomren et al. Peden et al. have reported that negative eccentric annuli are easier to clean compared to the concentric ones. Huque et al. (2020a) have reported the higher the positive eccentricity the poorer is the hole cleaning for the same flow rate of drilling fluid based on their CFD model made for a horizontal wellbore. Abbas et al. have made similar observation as Huque et al. experimentally for a horizontal test section using water-based test fluids. Rabia has found that concentric annulus provides the best cuttings carrying capacity of drilling fluid. He has further found the effect of eccentricity in vertical annulus small and oscillatory in nature while it has more impact on cleaning highly deviated wellbores.

2.7. Inclination

Iyoho (1980), Tomren et al. (1986), Rabia (1989), Sifferman and Becker (1992), Campos (1995), Azar and Sanchez (1997), Li and Walker (1999), Adari et al. (2000), Ahmed et al. (2010), Duan et al. (2006), Qahtani and Amanullah (2010), Ytrehus et al. (2018), Zhang (2015), Reda et al. (2018), Sayindla (2018), Deshmukh and Dewangen (Deshmukh and Dewangan, 2022) and, Rasool and Aadnøy (Rasool Khosravanian, 2022) have investigated the impact of inclination on cuttings transport. While Iyoho, Tomren et al., Adari et al., Ahmed et al., Sifferman and Becker and, Rasool and Aadnøy have identified inclination as one of the major parameters affecting cuttings transport, Duan et al. and Sayindla have found a minor impact of inclination on cuttings transport. Ytrehus et al. have observed the existence of a critical inclination angle for hole cleaning without rotation of inner string (<60°) below which hole cleaning has significantly improved. This critical angle is inversely related to RPM and drilling fluid flow rate. Zhang, and Deshmukh and Dewangen have reported 30° – 60° inclination the most difficult region for cuttings transport due to unstable cuttings bed (avalanche) and dramatic changes in cuttings moving patterns. Rasool and Aadnøy have identified 35° –60° as most challenging while vertical (0° – 35°) and near-horizontal (60° – 90°) wells to be less challenging to clean. Rabia has found this difficult angle range to be 40° – 60° while Li and Walker have reported this difficult to clean inclination close to 60°. They have recommended to avoid tangent section of around 60° and suggested to keep the build rate to 15° - 20°/30 m. Sifferman and Becker have reported stable cuttings bed between 60° and 90° inclinations. Azar and Sanchez have observed 65° as the onset for challenging hole cleaning that demands higher hydraulic requirements. Tomren et al. have reported observing cuttings bed formation at inclinations larger than 10° while Qahtani and Amanullah have observed cuttings bed at inclinations larger than 30°. Reda et al. have shown inverse relation between inclination and hole cleaning efficiency through their parametric study using a statistical model. Rabia has pointed out that the impact of inclination on hole cleaning is dependent on eccentricity of the drillstring.

2.8. Rotation of drillstring (RPM)

Iyoho (1980), Tomren et al. (1986), Peden et al. (1990), Rabia (1989), Sifferman and Becker (1992), Campos (1995), Azar and Sanchez (1997), Larsen et al. (1997), Saasen (1998), Ravi and Hemphill (2006), Duan et al. (2006), Bilgesu et al. (2007), Ozbayoglu et al. (2008), Yu et al. (2007), Ahmed et al. (2010), Nazari et al. (2010), Qahtani and Amanullah (2010), Sorgun (2010), Li and Luft (2014a), Zhang (2015), Ytrehus (Ytrehus et al., 2020, 2021a), Benjamin (Werner, 2018), Sayindla (2018), Reda et al. (2018), Huque et al. (2020b), Deshmukh and Dewangen (Deshmukh and Dewangan, 2022), Rasool and Aadnøy (Rasool Khosravanian, 2022) and Abbas et al. (2022) have studied the impact of RPM or inner string/drillstring rotation on cuttings transport.

Iyoho, Tomren et al., Larsen et al., and Ahmed et al. have reported an insignificant effect of RPM on cuttings transport based on their experiments with water-based systems, while Sayindla has reported RPM more influential on cuttings transport than inclination from her experiments with three different OBM samples. Zhang has reported RPM having the highest influence for horizontal well cleaning when ROP is low. Rasool and Aadnøy have also considered RPM an effective aid in cleaning horizontal well section. Yu et al. have reported the impact of RPM significant on cuttings transport as well. Saasen has argued that RPM will remove more cuttings from the cuttings bed formed in a WBM compared to that formed in an OBM. Peden et al. (1990), on the other hand, have observed an insignificant effect of RPM in large annulus while they have observed a significant improvement in cuttings transport by RPM for small annulus. Sifferman and Becker have reported a moderate effect of RPM on cuttings transport with the highest effect in horizontal wells for small cuttings (2 mm) and low ROP (15.2 m/h). Ravi and Hemphill have reported RPM to be an important hole cleaning parameter especially in eccentric annulus where the drilling fluid flows preferentially through the wider annulus in the absence of drillstring rotation. Duan et al. experimentally and Bilgesu et al. using CFD simulation have reported a positive role of RPM in transporting smaller-sized cuttings. Benjamin has reported high fluid flow rate and RPM to be the two dominating parameters for cuttings removal. Based on the comparative study of an OBM and a WBM, he has reported RPM having a superior effect on cuttings transport than flow rate. Rabia has reported RPM having greater impact in cuttings removal under laminar flow due to centrifugal force created by drillpipe rotation on the cuttings while RPM has small impact on cuttings transport under turbulent flow. Qahtani and Amanullah (2010) have also reported that pipe rotation and/or reciprocation may be necessary for efficient hole cleaning under laminar flow.

Sorgun has experimentally observed the significant impact of RPM on cuttings transportation for deviated/horizontal wells using water-based fluid systems. The positive impact of RPM on hole cleaning is more visible with an increase in fluid viscosity as was also observed by Ozbayoglu et al. It is further observed that RPM significantly reduces cuttings bed thickness and required minimum flow rate to prevent cuttings bed formation in an eccentric annulus. However, Sorgun has observed a certain RPM value (40 RPM) above that the influence of RPM on cuttings transport is negligible. Rabia, Ozbayoglu et al. and, Deshmukh and Dewangen have made a similar observation of a certain RPM as well. Ytrehus et al. have observed that the hole cleaning performance of the OBM improves significantly with drillstring rotation for intermediate inclination (48°) as mentioned earlier. Parametric study of Reda et al. has shown a direct relationship between RPM and hole cleaning efficiency. Abbas et al. have also recommended drill string rotation for efficient cleaning of horizontal well. However, Li and Luft have pointed out that high RPM might cause premature drillpipe failure under cyclic load, casing wear or open hole mechanical failure.

2.9. *Rate of penetration (ROP)*

Iyoho (1980), Rabia (1989), Sifferman and Becker (1992), Campos (1995), Azar and Sanchez (1997), Larsen et al. (1997), Li and Walker (1999), Li et al. (2004), Bilgesu et al. (2007), Qahtani and Amanullah (2010), Li and Luft (2014a), Zhang (2015), Reda et al. (2018) and Sayindla (2018) have investigated the impact of ROP on cuttings transport.

Iyoho, Campos, Azar and Sanchez, and Bilgesu et al. have identified ROP as a major drilling parameter affecting downhole cuttings concentration. However, Rabia and, Sifferman and Becker have reported the effect of ROP minor. Larsen et al., Li and Walker, Zhang, Reda et al. and Li et al. have observed a positive relationship between ROP and cuttings concentration i.e., increase in ROP increases cuttings concentration while keeping the other parameters unchanged. Qahtani and Amanullah have further pointed out too high ROP leading to high Cc can result in loss of cleaning ability of the drilling fluid. Li and Luft have recommended optimizing ROP to minimize the hole cleaning cost. Sayindla has observed higher impact of RPM on hole cleaning for lower ROP compared to higher ROP during her experiments with oil-based drilling fluids. She has further observed higher annular frictional pressure drop (or ECD for practical drilling operations) with higher ROP.

2.10. *Temperature*

Yu et al. (2007), Qahtani and Amanullah (2010), and Zhang (2015) have studied the temperature effect on cuttings transport. Yu et al. have reported temperature has a significant influence on cuttings transport as a change of temperature results in a change of drilling fluid rheological properties which, in turn, influences the viscous drag forces exerted on the drilled cuttings. They have reported a reduction of cuttings concentration with increasing temperature based on their experiments with water-based non-Newtonian test fluids (negative exponent in their developed statistical model for the relative temperature parameter). Zhang has also observed a decrease in cuttings concentration with an increase in temperature for non-Newtonian water-based test fluid with non-rotating test string due to diminishing shear thinning property of the test fluid and reduction in the gel-type bonding between packed cuttings with increase in temperature. However, he has reported no impact of temperature on cuttings transport if string rotation is present due to re-suspension of cuttings by the rotating string. Qahtani and Amanullah have reported a reduction in plastic viscosity due to elevated temperature.

It is quite evident from the literature survey above that cuttings transport is a complicated phenomenon involving many variables that are inter-dependent on each other. In addition, varying findings are reported by different research groups which points out to the need of a methodical data analysis approach such as EDA. There is no universally accepted theory that can describe all the observed behavior during cuttings transport (Rasool Khosravanian, 2022). Campos (1995) has pointed out the challenges and difficulties in developing a mathematical model taking care of all the different variables. Li and Luft (2014b) have highlighted the lack of satisfactory software, even after decades of research on cuttings transport, that can easily be implemented in the field without high computational expense. They have also pointed out the limitations of the empirical models with regards to prediction accuracy due to the presence of multiple variables in the cuttings transport process. Deshmukh and Dewangen (Deshmukh and Dewangan, 2022) have pointed out the possibility of using artificial intelligence (AI) algorithms to optimize the different drilling parameters to ensure proper borehole cleaning.

3. Experimental data

A total of 797 experimental observations are collected from different research groups that show the impact of different test parameters on cuttings concentration. The research groups can be divided into two groups – one that has used the TUDRP (The University of Tulsa Drilling Research Projects – a non-profit industry-university cooperation located in Tulsa, USA) test facility and the other one that has used the SINTEF (an independent research organization headquartered in Trondheim, Norway) test facility.

Ahmed et al. (2010) have published the first experimental dataset based on the work of Sagheer M. (Sagheer, 2009). They have collected the experimental data using PAC/water solution (described by the Power Law rheological model) for three different inclinations in an eccentric test section of approx. 26 m in length. The experimenters have used three different annulus sizes in their experiment.

Iyoho (1980) has gathered the second dataset using four different water based test fluids of different densities and different Power Law rheological constants. He has published the dataset collected both in concentric and eccentric annuli using a 12.2 m long test section for inclinations ranging from 0° to 90°.

Yu et al. (2007) have published the third dataset gathered using three water based test fluids following Bingham rheological model. They have varied the test temperature and collected the experimental data for horizontal and deviated inclinations using a 17.5 m long test section. The test pressure is 138 bar.

Zhang (2015) has collected the fourth data set using water in a fully eccentric test section of approx. 27 m for 30°, 45°, 50°, 55°, 60° and 90° inclinations. He has collected the experimental data under ambient conditions.

Ytrehus et al., 2020, 2021a, 2021b have published the fifth and sixth datasets using field used water and oil-based muds (described using the Herschel-Bulkley rheological model) under ambient conditions. They have used a 10 m long test section and three field representative inclinations namely 48°, 60° and 90°. The research group has chosen the test section dimensions such that the experimental results are scalable to 8 ½″ and 12 ¼″ section drilling.

Table App 1 in the Appendix summarizes the six experimental datasets that are collected using different experimental setup. It is quite evident from this table that the database used in the current work consists of diverse datasets. It has experimental data for seven different annulus sizes, seven different eccentricities, 12 different ROPs, 12 different RPMs, 23 different flow rates, 15 different inclinations, four different cuttings sizes and cuttings densities, four different temperatures and for both oil and water-based test fluids.

4. Data processing and outlier detection

The collected 797 observations are searched for duplicates using data profiling. 21 duplicate observations are found and removed from the dataset. Further averaging of cuttings concentration (Cc) and test fluid density values corresponding to repeated tests has reduced the total number of observations by 64. The total number of observations available for detecting outliers is **712**. Based on 1.5 * IQR (interquartile range) criteria applied to cuttings concentration experimental values, the following limits for outlier detection are calculated:

$$\mathrm{Cc} < 0.0\% \text{ or } \mathrm{Cc} > 26.1\% \rightarrow \text{outlier} \quad (1)$$

The above criterion detects 39 observations as outliers. Fig. 1 shows the corresponding box plot with the upper whisker at 25.71%.

It is to be noted that the criterion 1.5*IQR is based on symmetry as we are deducting the same amount from the lower quartile that we are adding to the upper quartile. Hence this criterion can flag many regular observations as outliers for asymmetric distributions (Rousseeuw and Hubert, 2018) such as the current Cc distribution (right-skewed, skewness: 1.68 i.e. highly skewed - a brief explanation of skewness is presented in sec. 5.1 Univariate analysis) shown in Fig. 2. Freedman-Diaconis binning rule is used in Fig. 2 as it is less sensitive to outliers and more suitable for data with heavy-tailed distributions.

Fig. 3 shows the detected outliers for the different annulus sizes, inclinations, eccentricities, flow rate of test fluid, test string rotation, and rate of penetration. Using the boxplots of Fig. 3 and the IQR criteria applied on Cc, a total of 92 potential outliers are detected. The detected outliers are carefully looked through using scatter plots made for the different sets of associated observations. Consideration is given to look at any change in the test parameters that can result in such deviation. After all careful consideration, the final number of outliers is found to be 10. The outliers are removed from the dataset. Thus, the final total number of observations becomes **702**.

Analysis of the 702 observations using data profiling shows that ~24% observations have less than 1% Cc for 1.95″, 2.26″ and 3.1″ annuli with the test section at vertical, deviated, and horizontal positions. Further analysis shows that horizontal and deviated test sections simulating horizontal and deviated wellbores can be cleaned completely to 0% Cc without rotation of the test string if the flow rate is sufficiently high. Otherwise, rotation of the string is required for 100% cleaning of the test section. Data profiling also shows that 6.4% of the collected dataset represents absolute vertical wellbore with 0° inclination of the test section and 5.3% of the dataset represents concentric wellbore with the test section eccentricity being zero. It further reveals that approx. 35% experimental observations are performed without rotating the test string.

Fig. 4 shows the 702 observations along with the testing facilities and test fluids used. It is quite visible that most of the experimental observations (~65%) are performed using water-based test fluids. Approx. 42% observations (SINTEF) are performed using field used drilling

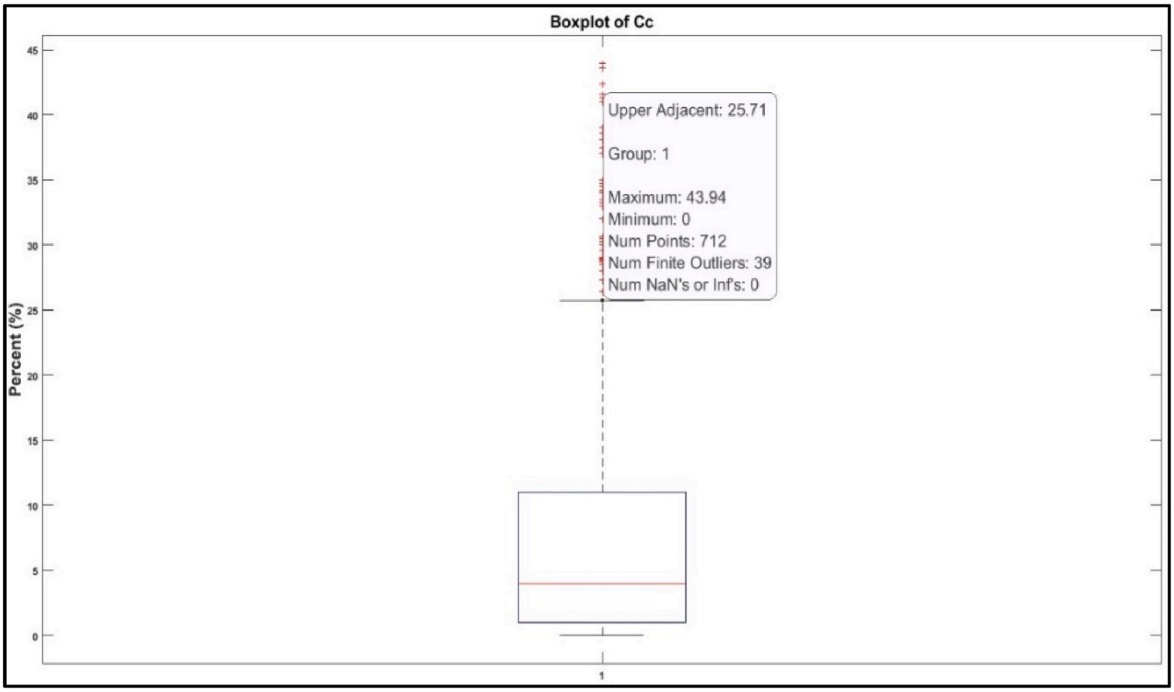


Fig. 1. Box plot showing potential outliers (as red crosses) based on IQR criteria. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

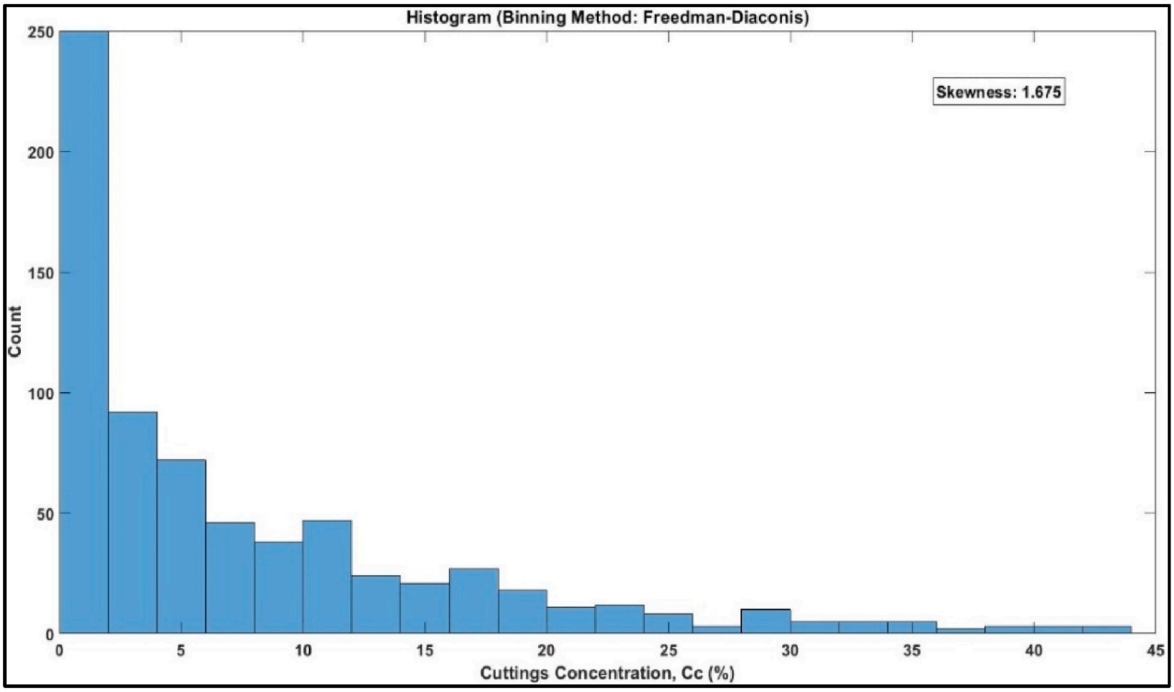


Fig. 2. Histogram of measured cuttings concentration after removal of duplicate observations and duplicate predictors.

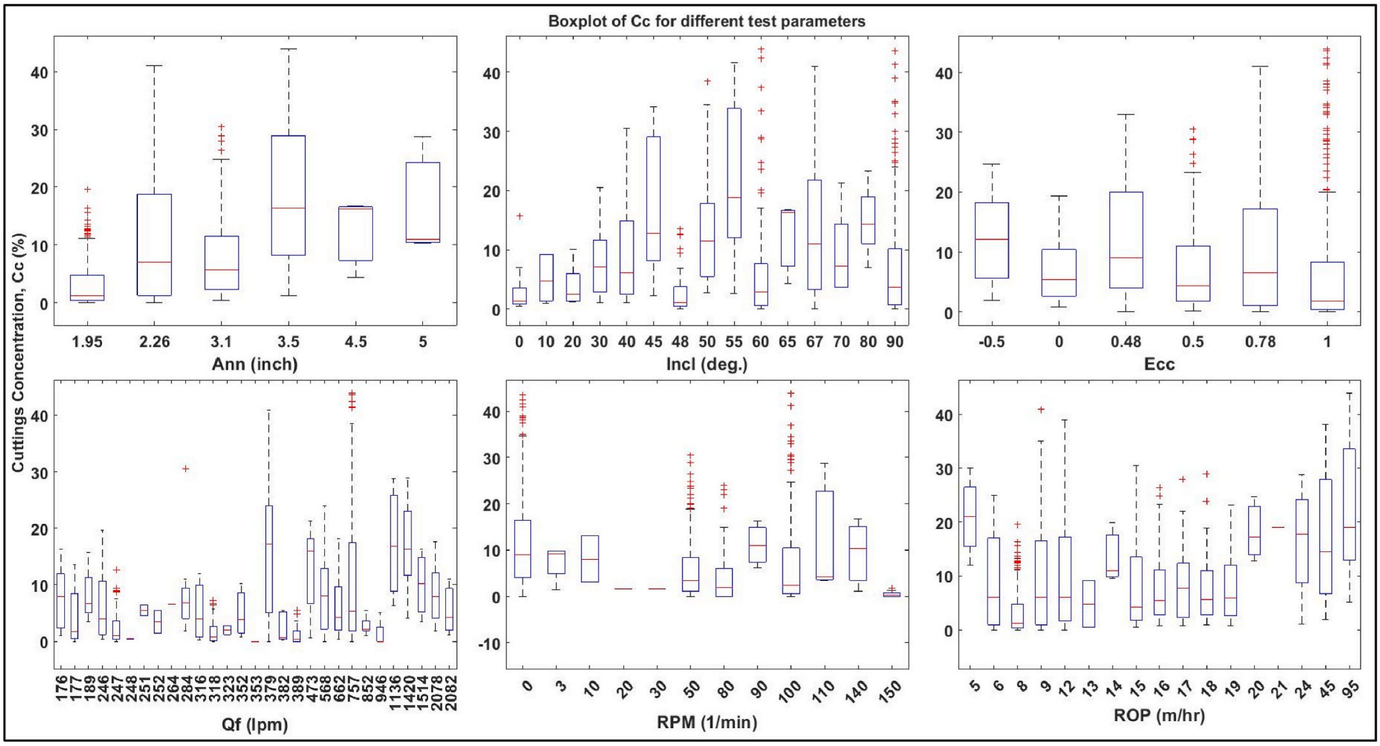


Fig. 3. Boxplots showing cuttings concentration for different annulus sizes (Ann), inclinations (Incl), eccentricities (Ecc), fluid flow rate (Qf), test string rotation (RPM) and rate of penetration (ROP).

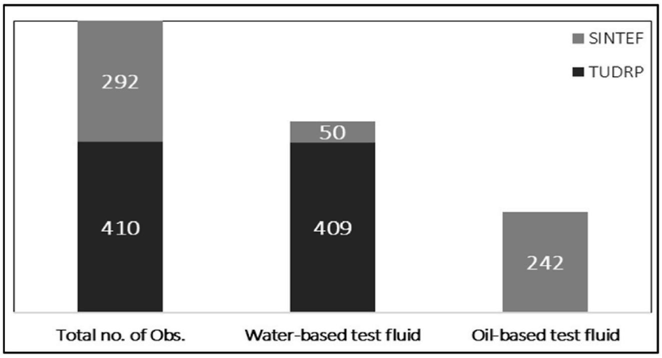


Fig. 4. The 702 observations to be used for further analysis and model development.

fluids.

5. Exploratory data analysis (EDA) of the experimental data

In the current work, EDA of the 702 observations is carried out in a two-fold manner: univariate analysis and multivariate analysis.

5.1. Univariate analysis

The univariate analysis aims at analyzing individual parameters in isolation to get a better insight into each of them using statistical summary and graphical technique such as histogram (Swamynathan, 2019). Table 1 shows the statistical summary of the 702 observations retained after outlier removal. The central tendency (mean, median, minimum, and maximum) and the spread (standard deviation, lower and upper quartiles) for each of the 11 test variables (annulus size (Ann), inclination (incl), eccentricity (Ecc), temperature (Temp), drilling fluid density (Rhof), apparent viscosity (Vapp), cuttings size (Cuts), cuttings density (Cuts), drilling fluid flow rate (Qf), test string rotation (RPM) and rate of penetration (ROP)) and the measured variable (cuttings concentration (Cc)) are presented in this table. Ann represents the diametrical difference between the test bore ID and the test string OD as mentioned earlier. Vapp is a calculated test parameter determined using the rheological properties of the test fluids together with the associated annulus dimensions and flow rates. Formulations presented in (Bourgoyne et al., 1986) and (Maglione et al., 1996) are used to determine this parameter. This calculated parameter can be used in determining drilling fluid's flow regime (laminar, transition and turbulent) using the Reynolds number criterion developed for Newtonian fluids (Bourgoyne et al., 1986).

Fig. 5 shows histograms for the 12 test parameters using Freedman-Diaconis binning rule for the 702 observations along with Kernel probability density function (pdf) estimates and skewness factors. A kernel distribution is a nonparametric representation of the pdf of a random variable defined by a smoothing function (such as a normal kernel function as in Fig. 5) and a bandwidth value, which controls the smoothness of the resulting density curve. Skewness is a measure of deviation from the symmetrical bell curve. If skewness is negative, the data spreads out more to the left of the median compared to the right. If skewness is positive, the data spreads out more to the right of the median than to the left. A normal distribution has zero skewness with the mean, median and mode of the data being the same value. If the skewness is between [−1, −0.5] or [0.5, 1], the data are moderately skewed and if it is larger than 1 or smaller than −1, the data are highly skewed (Dan, 2020). Fig. 5 shows clearly the asymmetric distribution of the different test parameters with both positive and negative skewness factors. The skewness of the data for the different parameters ranges from moderate to high. While inclination and eccentricity have negative skewness smaller than −0.5, the rest of the test parameters show positive skewness.

5.2. Multivariate analysis

Multivariate analysis aims at exploring the relationships among the variables with one another using graphical techniques such as scatter plot and statistical measures such as correlation coefficient (Swamynathan, 2019).

5.2.1. Stacked bar chart

Fig. 6 shows stacked bar charts of Cc for various operational parameters. Temperature is categorized as low (if temperature is in the interval [0,27) ^{o}C), medium (if temperature is in the interval [27,50) ^{o}C) and high (if temperature ≥50 °C) in this figure. Further, a well is categorized as vertical (if inclination is in the interval [0,30)^{o}), deviated (if inclination is in the interval (Tomren et al., 1986; Swamynathan, 2019)^{o}) and highly deviated (if inclination >60°) according to the observations made by Zhang (2015) and, Deshmukh and Dewangen (Deshmukh and Dewangan, 2022). Categorization of rest of the test parameters is shown in Fig. 6. Here, an overall increase in cuttings concentration is observed with increasing annulus size, inclination, ROP (also known as drilling rate) and cuttings density, and with decreasing RPM (test string rotation) and drilling fluid density. This is in accordance with the findings presented in sec. 2 *Literature survey*.

Comparison of the inclination and eccentricity stacked bar charts for Cc > 20% shows that these high Cc values are encountered for inclinations larger than 30° and for positive eccentricities. This is in accordance with the observations made by Iyoho (1980) and Tomren (Tomren et al., 1986) where they have pointed out positive eccentricity to be worst for hole cleaning when the inclination is larger than 55°.

The impact of flow rate, cuttings size and temperature on Cc is not quite clear from Fig. 6. However, less than 1000 lpm flow rate provides up to 2% cuttings concentration for more than one-third (253 observations) of the total observations as manifested by the first stacked bar on the left of the flow rate-based bar chart. 88% (223 observations out of 253 observations) of these observations involve the contribution of test string rotation. It is to be noted that reaching a concrete conclusion using the stacked bar chart is challenging as it rather shows the distribution of

Table 1
Statistical summary of the 702 experimental observations.

Statistical parameters	Experimental parameters											
	Ann (inch)	Incl (^{o})	Ecc (frac)	Temp (^{o}C)	Rhof (kg/m^{3})	Vapp (cP)	Cuts (mm)	Rhos (Kg/m^{3})	Qf (lpm)	RPM (rev. Per min)	ROP (m/hr)	Cc (%)
Mean	2.55	63.56	0.68	32.00	1234.64	55.02	3.39	2644.38	546.79	53.03	17.50	7.61
Standard deviation	0.63	26.52	0.37	15.02	257.52	55.88	2.14	11.82	413.37	48.47	19.93	8.86
Minimum	1.95	0.00	−0.50	26.00	998.15	1.00	1.30	2627.79	175.80	0.00	4.57	0.00
Lower quartile	1.95	48.00	0.50	27.00	998.70	1.00	1.30	2632.00	283.91	0.00	8.00	1.00
Median	2.26	60.00	0.78	27.00	1012.50	50.30	3.00	2650.00	386.70	50.00	9.14	4.11
Upper quartile	3.10	90.00	1.00	28.00	1481.93	87.11	6.35	2651.30	662.45	99.90	17.02	11.10
Maximum	5.00	90.00	1.00	82.00	1688.60	250.98	6.35	2667.00	2081.97	150.00	95.00	43.94

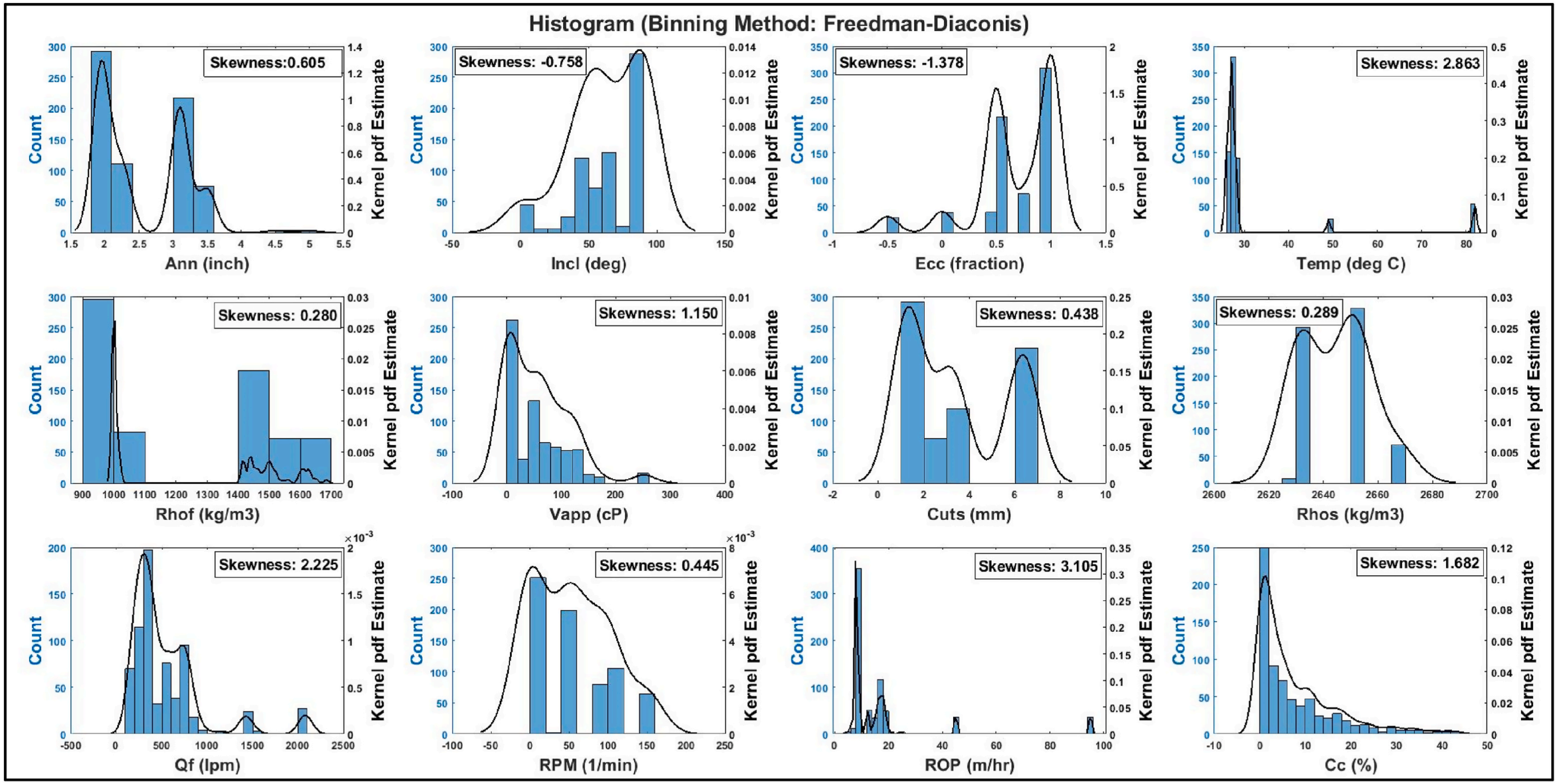


Fig. 5. Histogram, Kernel probability density function (pdf) estimates, and unbiased skewness factor of the 12 test parameters.

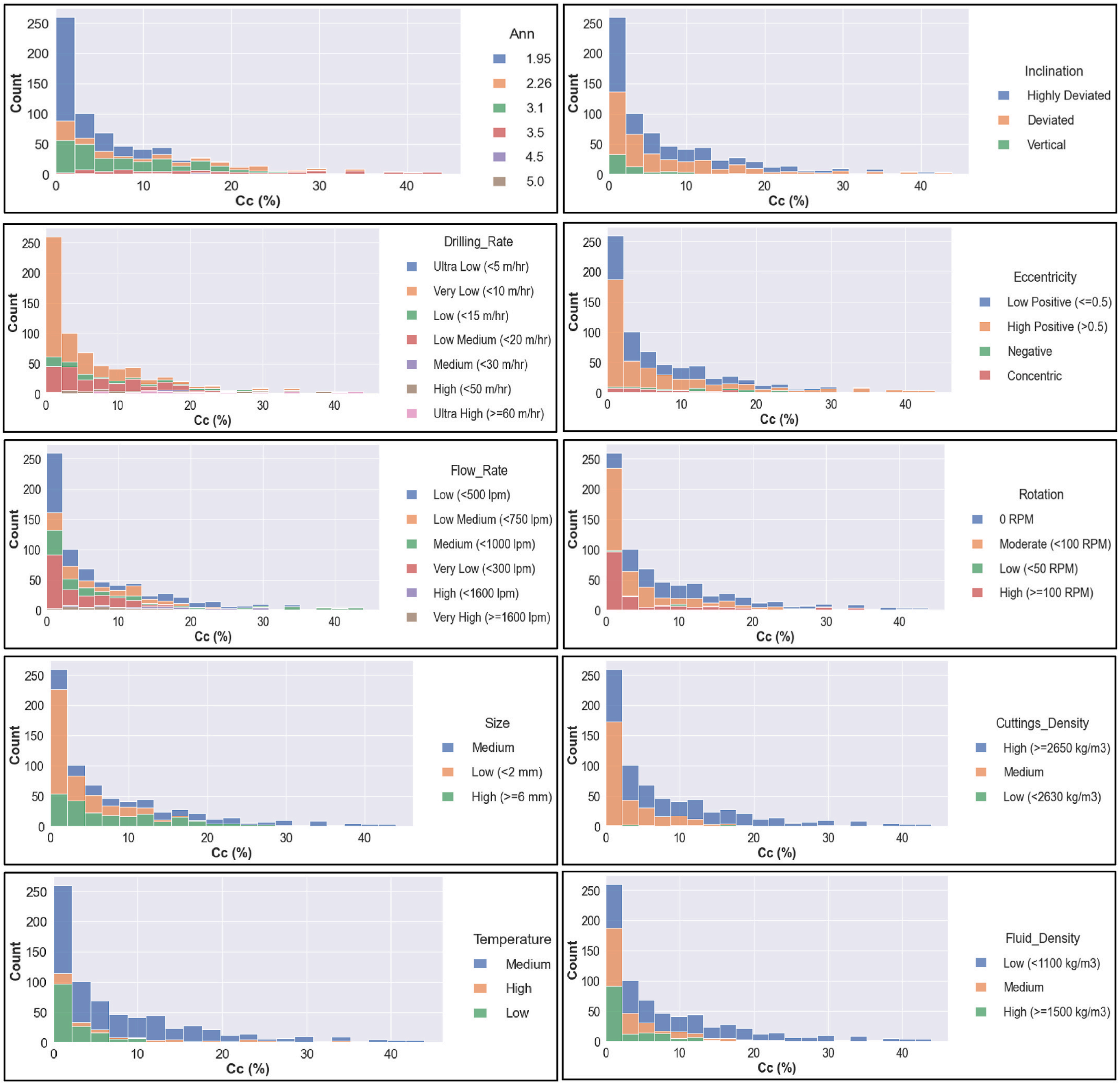


Fig. 6. Stacked bar chart showing cuttings concentration (Cc) for different annulus sizes, inclinations, eccentricities, ROPs, fluid flow rates, RPMs, cuttings sizes, cuttings densities, temperatures and fluid densities.

the different test parameters with respect to Cc, but not their relationship with Cc.

5.2.2. 6D scatter plot

To explore the interactions between different test parameters to find out their combined impact on Cc, 6D (data dimensions) scatter plots are made. Figs. 7–14 show these scatter plots where changes of Cc with drilling fluid flow rate (Qf) for different operational parameters are plotted. In these plots, the variation of Cc with Qf is presented for different annulus sizes (presented by different color schemes for the different annuli). Different values of ROP used for collecting the experimental observations are presented by varying the marker size on these plots (indicated by varying sizes of a circle in the legend). And finally, RPM values involved in all the observations are presented by different marker styles (left, right, up and down-filled arrows). The sixth dimension in each plot is represented by a categorized variable such as eccentricity, inclination and temperature.

The scatter plot in Fig. 7 shows the variation of Cc for different eccentricities presented in four different facets or subplots – concentric (if eccentricity = 0), negative eccentric (if eccentricity <0), low positive eccentric (if eccentricity in the interval (0,0.5]) and high positive eccentric (if eccentricity in the interval (0.5,1]) test sections for different annulus sizes (top plot) and for different inclinations (bottom plot). The annulus size 3.1″ (experiment performed by Iyoho (1980)) has experimental observations for all the four different eccentricities while the rest of the observations for the other annuli represented by different colours are performed using positive eccentric test sections. It is to be noted that the test string is displaced towards the high side of the test section to

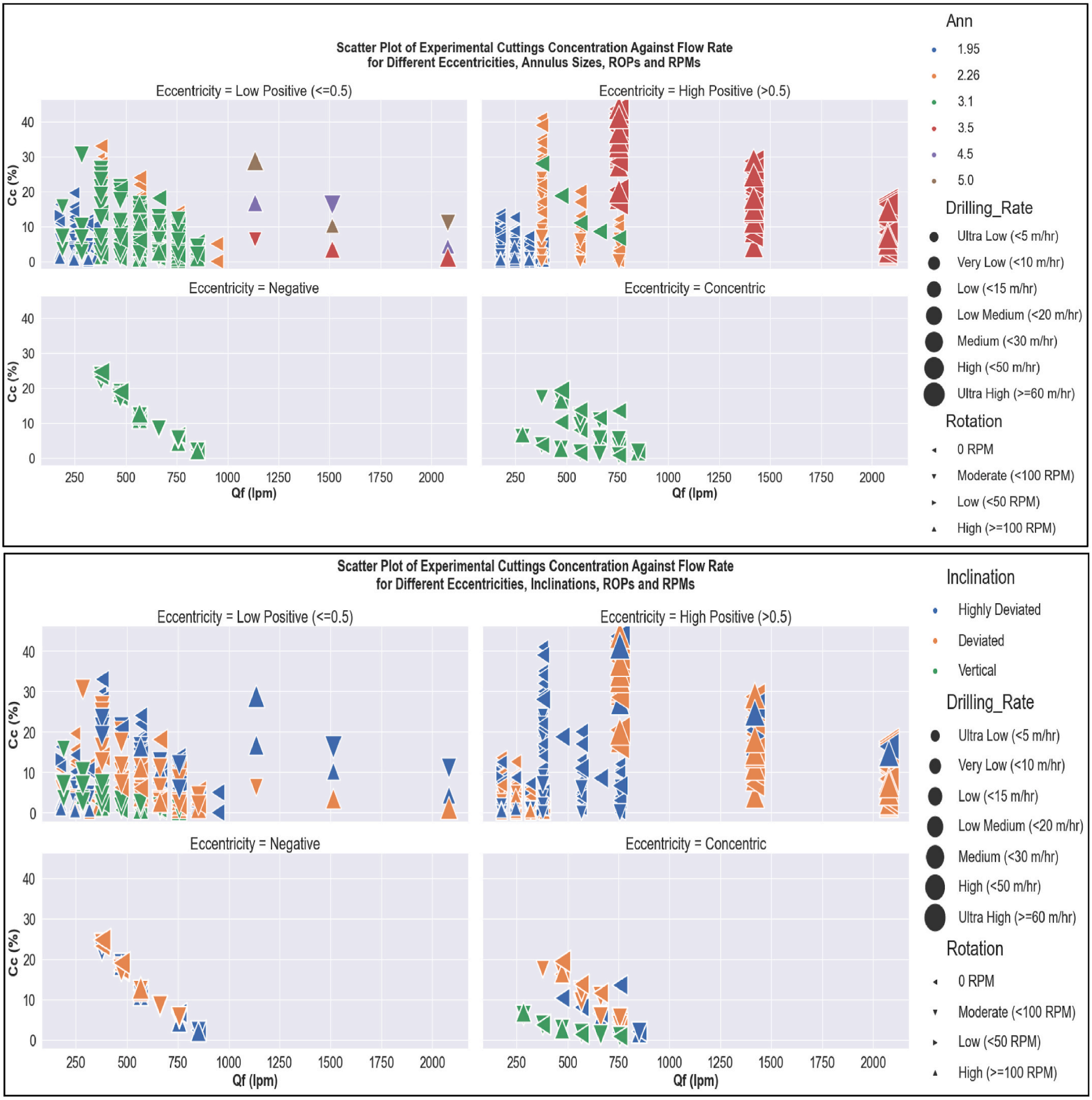


Fig. 7. 6D scatter plots showing changes in experimental Cc with flow rates for different eccentricities (subplots or facets) along with different annulus sizes, ROPs and RPMs (top plot), and along with different inclinations, ROPs and RPMs (bottom plot).

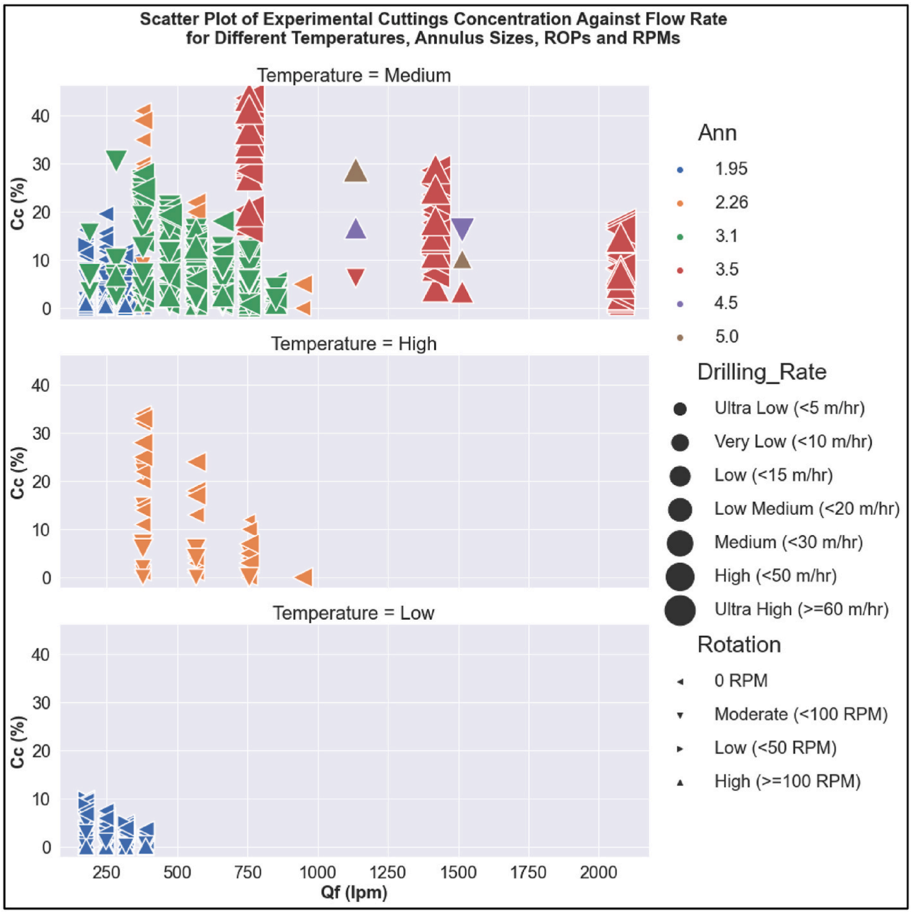


Fig. 8. 6D scatter plot showing changes in experimental Cc with flow rates for different temperatures (subplots or facets) along with different annulus sizes, ROPs and RPMs.

simulate a negative eccentric annulus while it is displaced towards the low side of the test section to simulate a positive eccentric annulus.

An overall decrease in Cc with increasing Qf is seen for all annulus sizes and all inclinations. A lower value of Cc for concentric vertical test section is observed compared to the non-vertical concentric test sections for the same flow rate and ROP. A possible explanation to this observation can be the absence and presence of cuttings bed in vertical and non-vertical wells respectively. In addition, an overall increase of Cc is observed for both deviated and highly deviated test sections with an increase in positive eccentricity. This is in line with the observation made by Abbas et al. for a horizontal test section where they have observed reduced cuttings transport ratio with increasing positive eccentricity (Abbas et al., 2022). A possible explanation, as pointed by Abbas et al., is the reduction of the axial drag force applied on cuttings (located on the cuttings bed) by drilling fluid with increasing positive eccentricity.

Fig. 7 shows two features – one is increase in inclination increases Cc for the same flow rate, ROP, annulus size and eccentricity. The other one is higher Cc values occur for the non-rotating cases compared to the rotating string cases for the same flow rate, ROP, annulus size, eccentricity and inclination (deviated/highly deviated). In addition, it is visible that the contribution of RPM in concentric and negative eccentric annuli to cuttings removal is not so significant as it is in the case of positive eccentric annuli. It is further observed that contribution of RPM for vertical wellbore cleaning is insignificant. Fig. App. 1 shows this quite clearly for an excerpt from the experimental dataset.

Fig. 8 shows an increase in Cc with increasing temperature for 1.95″ annulus size. However, it shows a decrease of Cc with increasing temperature for 2.26″ annulus size. For other annuli sizes, the temperature is kept unchanged. The reason for the observation with the 1.95″ annulus size (experiment performed by Ytrehus et al.) is the absence of string rotation and reduction in flow rate between 28 °C and 26 °C observations. It is to be noted that observations related to 1.95″ annulus size are collected at ambient temperature which varied at 26 and 28 °C. So, the temperature is not intentionally varied for these observations as is done for the observations related to 2.26″ annulus size. Further, most of the observations fall into the medium temperature range and here the impact of ROP, flow rate and RPM is quite visible on Cc, i.e., higher ROP at lower flow rate without string rotation produces higher Cc for the same annulus size.

Fig. 9 shows Cc for different inclinations. The categorization of inclination is performed in the same way as stated earlier. Fig. 9 shows inclination is varied from vertical to highly deviated for annulus size 3.1″, while the observations related to other annuli sizes are performed either at deviated or highly deviated or both types of inclinations. Cc is less in vertical orientation of the test section for 3.1″ annulus size

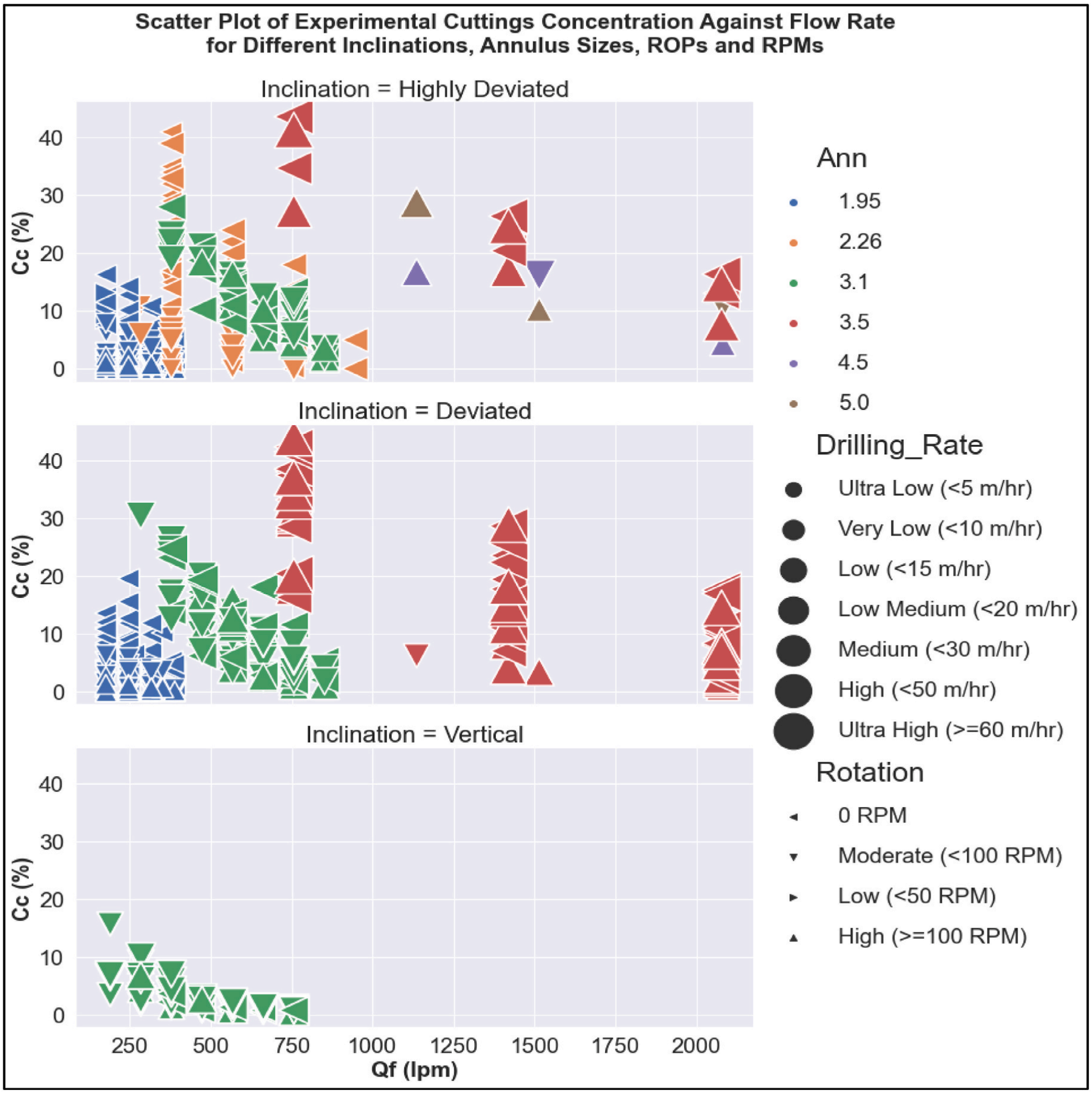


Fig. 9. 6D scatter plot showing changes in experimental Cc with flow rates for different inclination subplots or facets) along with different annulus sizes, ROPs and RPMs.

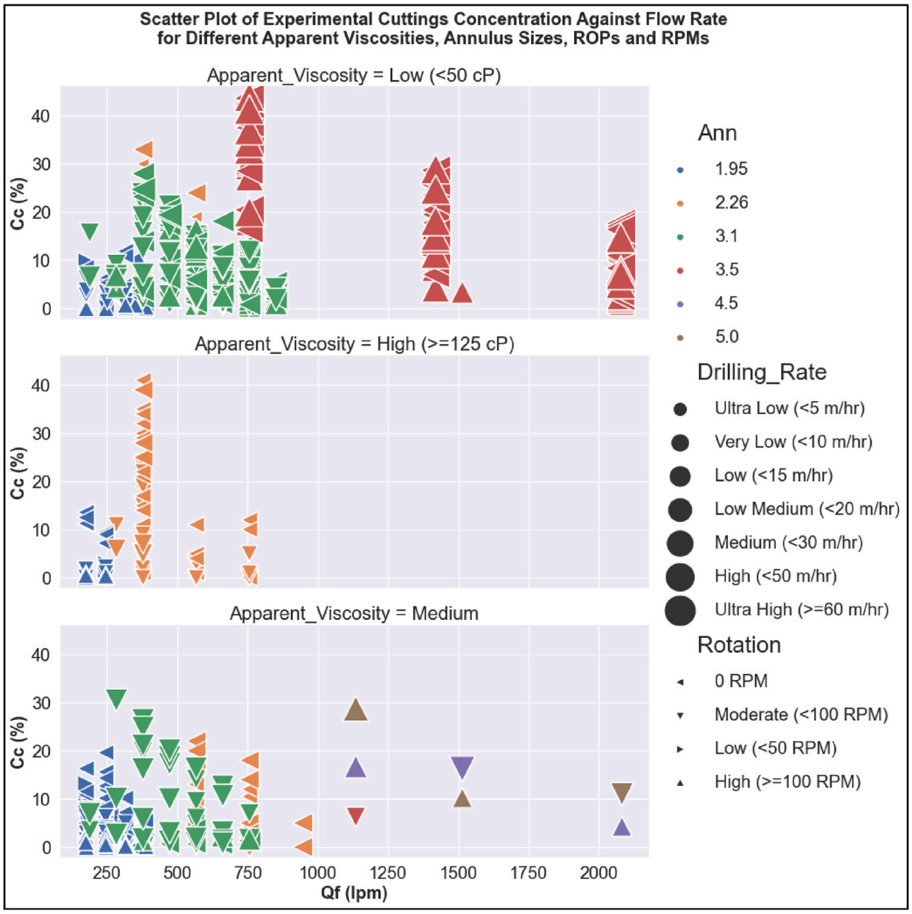


Fig. 10. 6D scatter plot showing changes in experimental Cc with flow rates for different apparent viscosities (subplots or facets) along with different annulus sizes, ROPs and RPMs.

compared to the two other types of inclination. No significant impact of string rotation on hole cleaning is observed for vertical test section as shown by Fig. 7. Like Figs. 8 and 9 shows the positive impact of flow rate and RPM on cuttings removal at deviated and highly deviated inclinations.

Fig. 10 shows apparent viscosity (low, medium, and high) on three different facets where changes in Cc with flow rate for different annulus sizes, ROP and RPM are presented using the scheme stated earlier. Higher flow rates are observed for low and medium apparent viscosity fluids compared to those of high apparent viscosity fluids in the collected experimental dataset. Further, the high viscosity fluids are used only for the annulus sizes 1.95″ and 2.26″ to simulate deviated and horizontal wells. An overall increase of Cc with increasing apparent viscosity is observed for all annulus sizes except 3.1″ and 3.5″ which show a reduction in Cc with increasing apparent viscosity. This is more visible from Fig. App. 2 upon use of an imaginary linear trendline on each subplot. Fig. App. 2 also shows the three different flow regimes (laminar, transition and turbulent) determined using Reynolds number following Bourgoyne et al. (1986) for the different annulus sizes. It is found from Fig. App. 2 that 1.95″ has laminar flow for most of the associated observations with a few observations being performed within the transition flow regime. While 2.26″ and 3.1″ (only two observations performed under transition flow regime) annulus sizes have observations performed in all the three flow regimes, 4.5″ and 5″ annulus sizes have no experimental observations performed in the turbulent flow regime like 1.95″ annulus size. 3.5″ annulus size has all observations performed under turbulent and transition flow regimes. It is perceived from these two scatter plots that sufficient viscosity is needed for efficient cuttings transport depending on inclination and that RPM plays a significant positive role in cuttings removal under all the three flow regimes for all the annulus sizes. A closer look incorporating inclination (Fig. 11) shows that low viscous fluid under turbulent flow with drill string rotation and high viscous fluid under laminar flow with drill string rotation provide better hole cleaning. It is to be noted from Fig. 11 that a drilling fluid with inadequate viscosity won't help cleaning a well even with high flow rates providing turbulent flow and with drillstring rotation.

Figs. 12 and 13 show the impact of cuttings size and cuttings density using facet plots respectively. Annulus size 1.95″ has the smallest cuttings size while 3.1″ annulus size has the largest cuttings size for the current dataset. Cc values are lower for 1.95″ annulus size compared to those of 3.1″. However, it is to be noted that ROP is higher for 3.1″ annulus size observations than that for 1.95″ annulus size. In addition, test fluids used for the 3.1″ observations are much lighter than those of 1.95″ annulus size observations (ref. Table App 1). The effect of RPM seems higher on smaller cuttings while flow rate has a greater impact on

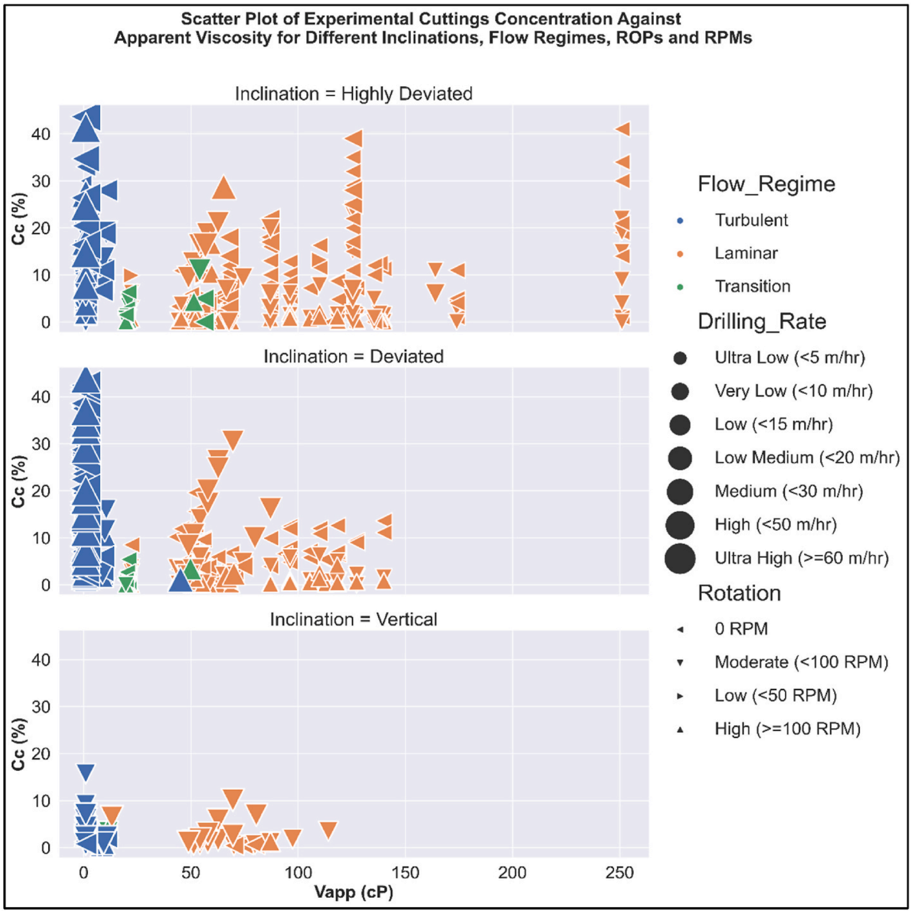


Fig. 11. 6D scatter plot showing changes in experimental Cc with flow rates for different inclinations (subplots or facets) along with different apparent viscosities, flow regimes, ROPs and RPMs.

larger cuttings with respect to hole cleaning. For the medium sized cuttings (3 and 3.35 mm), the influence of flow rate is stronger than rotation for the bigger particles while rotation together with flow rate provides better hole cleaning for the smaller cuttings. Larger cuttings have larger area and hence larger drag force acting compared to the smaller cuttings for the same flow rate of drilling fluid. Also, smaller cuttings have lower buoyancy compared to the bigger particles due to smaller particle volume and hence can easily form cuttings bed which can be disturbed and redistributed into suspension by drill string rotation.

Fig. 13 shows most observations are performed with heavier cuttings. The heavier cuttings have larger Cc values compared to the lighter ones. Flow rate has a higher impact on heavier cuttings while RPM influences the transport of lighter cuttings more. Heavier cuttings have higher slip velocities compared to those of lighter cuttings due to higher cuttings density (assuming same cuttings size) and hence can be effectively transported out of the wellbore if sufficient drilling fluid flow rate is available.

Fig. 14 shows the impact of test fluid density on Cc on different facets. Majority of the test fluids have low density. Observations related to 1.95″ annulus size have medium and high-density test fluids while observations related to 2.26″ annulus size have low and medium density test fluids. It is seen that the heavier test fluids provide better hole cleaning compared to lighter fluids. This can be due to the fact heavier fluids provide more buoyancy to cuttings compared to that by lighter fluids and hence lower the slip velocity of cuttings. This is in line with the observations made by Sifferman and Becker, Azar and Sanchez, and Larsen et al. as outlined in sec. 2 *Literature survey*. In addition, Fig. 14 shows string rotation has higher impact on hole cleaning with high-density test fluids compared to lighter fluids. Also, it shows that higher flow rates for lighter fluids are used compared to those of heavier fluids.

5.2.3. Correlation

Correlation is a statistical bivariate analysis that measures the degree of association/relationship between two variables (i.e., the tendency of the variables to change together) using a statistic called the correlation coefficient. The correlation coefficient can assume values between [−1, 1] where ±1 indicates a perfect association between the two variables and 0 indicates no association. The value of the correlation coefficient indicates the degree of association or the strength of the relationship while its sign indicates whether the two variables change in the same direction (+sign) or opposite directions (- sign). Table App 2 shows the strength categorization of correlation coefficient which can be used as a guideline, but the actual categorization of the strength of relationship is dependent on the research context and its purpose while forming conclusions. It is to be mentioned that a correlation does not imply causation (Popovich, 2002), but causation always implies correlation (Bhandari, 2021).

Commonly used correlation coefficients are Pearson’s linear

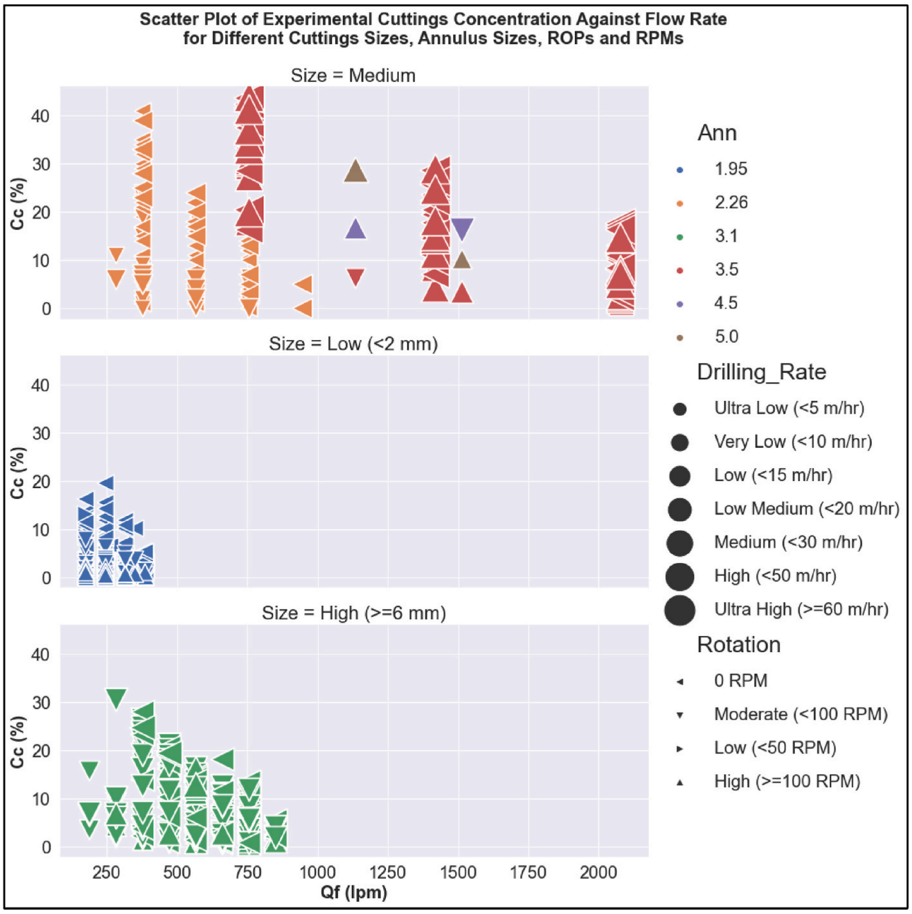


Fig. 12. 6D scatter plot showing changes in experimental Cc with flow rates for different cuttings sizes (subplots or facets) along with different annulus sizes, ROPs and RPMs.

correlation coefficient (r), Kendall's rank correlation coefficient (τ), and Spearman's rank correlation coefficient (ρ). Pearson's r is a parametric measure of correlation while Kendall's τ and Spearman's ρ are nonparametric measures of correlation between two variables. Pearson's r evaluates only the positive or negative linear relationship (constant rate of change) between two continuous variables that are normally distributed, while Kendall's τ and Spearman's ρ evaluate the monotonic relationship (variable rate of change) between two continuous or ordinal variables without assuming any specific probability distribution of the variables (Xiao et al., 2016; Rooney, 1027). Pearson's r is sensitive to outliers while the two nonparametric correlation coefficients are robust against outliers (Croux and Dehon, 2010). Between the two nonparametric correlation coefficients, Kendall's τ is preferred due to its better robustness against outliers (Chok, 2010) and better efficiency (Croux and Dehon, 2010) compared to Spearman's ρ. Mathematically Kendall's τ can be expressed as follows:

$$\tau = \frac{2K}{n(n-1)} \tag{2}$$

Here, n = number of observations for each parameter.

$K = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} f(X_i, X_j, Y_i, Y_j)$ and

$$f\left(X_i, X_j, Y_i, Y_j\right) = \begin{cases} 1 \text{ if } \left(X_i - X_j\right)\left(Y_i - Y_j\right) > 0 \\ 0 \text{ if } \left(X_i - X_j\right)\left(Y_i - Y_j\right) = 0 \\ -1 \text{ if } \left(X_i - X_j\right)\left(Y_i - Y_j\right) < 0 \end{cases} \tag{3}$$

X, Y = parameters for which Kendall's τ is sought for

Based on the findings from the relevant literature mentioned earlier and the asymmetric distribution of the experimentally measured parameters including Cc presented in Fig. 5, Kendall's τ is used to find the correlation between the different experimental parameters using the 702 experimental observations in the current work. Figs. App. 3 and 4 show Kendall's τ as heatmaps for the different experimental parameters for different annulus sizes and inclinations respectively. The corresponding p-value (null hypothesis, H_o: no correlation and significance level, α: 0.05) for each correlation coefficient are calculated using a permutation test – a nonparametric test where the variable of interest is randomly sampled using possible permutations without replacement (Berk, 2021).

Since 4.5″ and 5″ annulus sizes have only three observations each, they are excluded from Fig. App. 3. Fig. App. 3 shows only parameters that are changed during experimentation with a particular annulus size. It is seen that flow rate is negatively related to Cc for a particular annulus size and the effect of flow rate on Cc shows an overall increase as the annulus size increases. This is also reflected in Table 2 which shows the strength of correlation between Cc and different test parameters for the different annulus sizes based on Table App 2. The annulus size 2.26″ involves observations with three different temperatures. Fig. App. 3 shows a statistically insignificant negative monotonic relationship

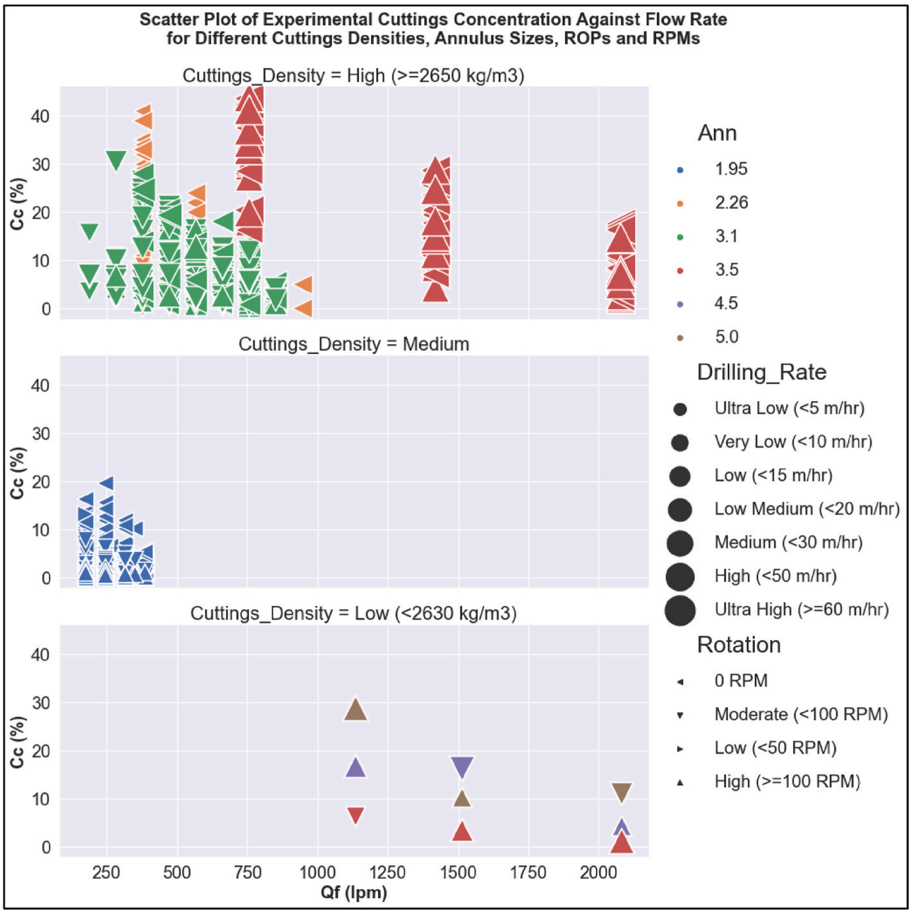


Fig. 13. 6D scatter plot showing changes in experimental Cc with flow rates for different cuttings densities (subplots or facets) along with different annulus sizes, ROPs and RPMs.

between Cc and temperature for this annulus size. However, the observations related to 1.95″ annulus size show a positive monotonic (statistically significant) relationship between temperature and Cc. But the temperature for 1.95″ annulus size experiments is the ambient temperature when the experiments are performed at the SINTEF facility with different test fluids at different times. It is further noted that temperature is positively related to fluid density and apparent viscosity for the 1.95″ annulus dataset while it is negatively related to these two variables for the 2.26″ annulus dataset. In addition, it is noted that flow rate and temperature are negatively related for 1.95″ annulus size and hence an increase in temperature results into an increase in Cc as flow rate decreases with increase in temperature for this annulus size. Table 2 further shows that string rotation has stronger impact on cuttings transport in small annulus while its influence decreases as the annulus size increases. This is in agreement with Peden et al. (1990). On the other hand, influence of ROP increases as the annulus size increases. ROP has moderate positive correlation (0.3538) with Cc when calculated across all the different annulus sizes in the current database.

Fig. App. 3 shows Rhof, Rhos and Ecc have correlation coefficients 1 for annulus size 3.5″. This annulus size comprises of experimental data from Zhang and Ahmed et al. where they have unchanged values of these test parameters in their respective experimental investigations and hence the correlation coefficients between these parameters for the overall 3.5″ annulus size observations become 1.

Fig. App. 4 shows Kendall's τ for vertical, deviated and highly deviated test sections. Like Fig. App. 3, Fig. App. 4 shows only parameters that are changed during experimentation. Drilling fluid flow rate plays a significant role in hole cleaning in vertical test sections while test string rotation is dominant for deviated and highly deviated test sections. This is also evident from Table 3. Further, the role of eccentricity on hole cleaning is negligible (statistically insignificant) for vertical test sections which is in accordance with the observation made by Rabia. Table 3 shows a weak negative relationship between Cc and eccentricity for other inclinations. Close observation of the heatmap in Fig. App. 4 reveals that as eccentricity increases, so does test string rotation (statistically insignificant for deviated test sections) which is found to be the dominant factor for cleaning deviated and highly deviated test sections. In addition, it is noticed from the heatmaps that ROP decreases with increasing eccentricity in deviated/highly deviated test sections for the current dataset. A similar observation is made for Cc, temperature and test string rotation. Fig. App. 4 shows a positive relation between Cc and temperature for deviated and highly deviated test sections. However, temperature has a negative bearing with RPM – meaning with increasing temperature, RPM decreases for the non-vertical test sections in the current dataset and hence Cc increases with increasing temperature. Fig. App. 4 also reveals one well known fact (ref. sec. 2 *Literature survey*) that increasing Rhof will cause the economic penalty of reduced ROP through the negative correlation coefficient between ROP and Rhof for all the three inclinations even though it has a positive influence on hole

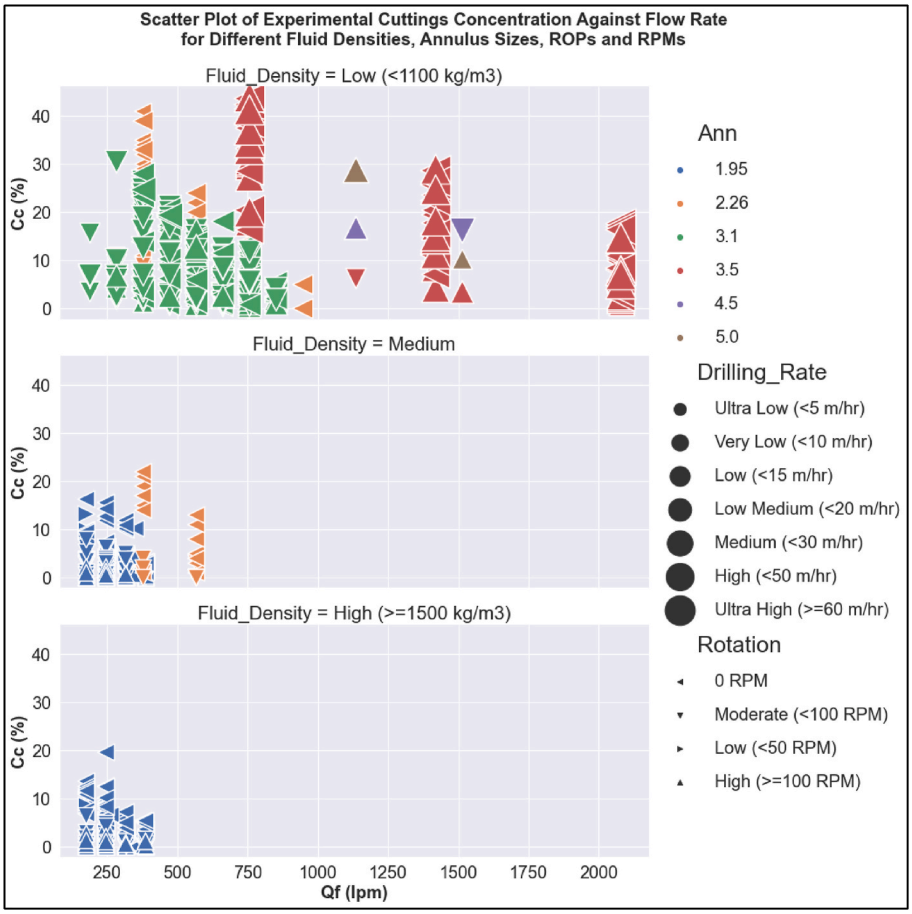


Fig. 14. 6D scatter plot showing changes in experimental Cc with flow rates for different fluid densities (subplots or facets) along with different annulus sizes, ROPs and RPMs.

Table 2
Correlation between Cc and different test parameters for different annulus sizes.

Experimental parameters	Annulus size (")			
	1.95	2.26	3.1	3.5
Inclination (°)	Insignificant Negative	Insignificant Negative	Moderate Positive	Moderate Positive
Eccentricity (fraction)	Weak Negative	Insignificant Negative	Weak Negative	Weak Positive
Temperature (°C)	Weak Positive (ambient temp. variation)	Insignificant Negative	Unchanged (27)	Unchanged (27)
Fluid density (Kg/m^3)	Insignificant Positive	Weak Negative	Weak Negative	Weak Positive
Apparent Viscosity (cP)	Weak Positive	Insignificant Positive	Weak Negative	Weak Negative
Cuttings size (mm)	Unchanged (1.3)	Unchanged (3.35)	Unchanged (6.35)	Weak Negative
Cuttings density (Kg/m^3)	Unchanged (2632)	Unchanged (2650)	Unchanged (2651.3)	Weak Positive
Flow rate (lpm)	Weak Negative	Moderate Negative	Moderate Negative	strong Negative
String rotation (rev/min)	Strong Negative	Moderate Negative	Insignificant Negative	Weak Negative
ROP (m/hr)	Unchanged (8)	Insignificant Positive	Weak Positive	Weak Positive

Table 3
Correlation between Cc and different test parameters for the different inclinations.

Experimental parameters	Inclination (°)		
	Vertical [0,30)	Deviated [30,60]	Highly deviated (60,90]
Annulus size (")	Unchanged (3.1)	Strong Positive	Moderate Positive
Inclination (°)	Weak Positive	Weak Negative	Weak Negative
Eccentricity (fraction)	Insignificant Negative	Weak Negative	Weak Negative
Temperature (°C)	Unchanged (27)	Weak Positive	Weak Positive
Fluid density (Kg/m^3)	Weak Negative	Moderate Negative	Moderate Negative
Apparent Viscosity (cP)	Weak Negative	Moderate Negative	Insignificant Negative
Cuttings size (mm)	Unchanged (6.35)	Moderate Positive	Moderate Positive
Cuttings density (Kg/m^3)	Unchanged (2651.3)	Strong Positive	Moderate Positive
Flow rate (lpm)	Strong Negative	Weak Positive	Weak Positive
String rotation (rev/min)	Weak Positive	Moderate Negative	Moderate Negative
ROP (m/hr)	Insignificant Positive	Moderate Positive	Moderate Positive

cleaning (evident through the negative correlation coefficients for all the three inclinations between Rhof and Cc).

Table 3 shows Qf to be more influencing in cleaning vertical wellbore while RPM is more influential in cleaning non-vertical wellbores. It is intuitive as drill string rotation in non-vertical wells disturbs the cuttings bed formed and contributes to redistributing the bed into suspension. It is to be noted that Table 3 shows positive correlation coefficient between Cc and Qf for non-vertical test sections which is counter-intuitive and against what is found during the literature survey. Close observation of Fig. App. 4 reveals that Qf is positively related to ROP which, in turn, is positively related to Cc for the non-vertical test sections. This explains the positive correlation coefficient for Cc and Qf for the non-vertical test sections in the current dataset. Similar reasoning holds for the correlation coefficients between Cc and Cuts. Further, Incl, Ecc and Vapp are observed to be negatively correlated to ROP. Table 3 shows that apparent viscosity plays a more significant role in cleaning deviated wellbores compared to vertical and highly deviated wellbores. In addition, Table 3 shows drilling fluid density having more influence in cleaning non-vertical wells compared to the vertical ones.

The above EDA analysis reveals that the experimental data is nonparametric as the experimental parameters have asymmetric distribution. It is hence quite evident that a nonparametric computational modeling method such as fuzzy logic (FL) can be used for modeling downhole Cc based on this experimental data. FL is assumption-free and can deal with imprecision and outliers in data. It resembles human reasoning in its modeling approach via the use of a rule base developed using observations. Chowdhury and Hovda (2022) have presented one such soft computational modeling of Cc using FL.

6. Conclusions

A literature survey is presented in the current paper to investigate the influence of different operational parameters (such as flow rate, ROP, RPM and temperature), cuttings and fluid parameters (such as density, cuttings size and fluid rheology) and geometrical parameters (such as annulus size, inclination and eccentricity) on downhole cuttings concentration. It is quite clear from the literature survey that cuttings transport is a complicated process involving many variables and hence cuttings transport modeling using conventional approach is challenging while its need for consideration during well planning/execution phases is obvious. Varying findings reported by different research groups points out to the need of a methodical data analysis approach such as exploratory data analysis or EDA (applied with success in different other fields) to analyze cuttings concentration experimental data.

797 experimental observations collected from six experiments performed by different research groups using TUDRP and Sintef test facilities are used in the current work. The collected datasets are processed and analyzed for outlier detection using inter-quartile range (IQR) criterion followed by careful judgement via use of scatter plots. 702 experimental observations obtained after data processing and outlier removal are used for exploratory data analysis (EDA). The EDA analysis is performed in a two-fold manner – univariate and multivariate analysis. Univariate analysis shows the asymmetry in data distribution for each experimental parameter. Multivariate analysis shows the interaction of the experimental parameters among themselves and their influence on downhole cuttings concentration, Cc. EDA of the current experimental data reveals the following major findings:

- Smaller Cc in concentric vertical wells compared to concentric non-vertical wells. An increase of Cc is observed for both deviated and highly deviated test sections with an increase in positive eccentricity
- Among the operational parameters, drilling fluid flow rate is found dominant in vertical wellbore cleaning while string rotation (RPM) is dominant in non-vertical wellbore cleaning. This is manifested by the corresponding values of Kendall's τ.
- Little impact of RPM in concentric vertical well and negative eccentric deviated/highly deviated well cleaning. However, RPM together with drilling fluid flow rate provides better cleaning of non-vertical wells with positive eccentricity.
- RPM has higher influence on cuttings transport in narrow annulus compared to that in wide annulus as manifested by the corresponding values of Kendall's τ. However, drilling fluid flow rate shows increasing contribution in cuttings removal as the annulus size increases.
- Low viscous drilling fluid under turbulent flow with drill string rotation and high viscous drilling fluid under laminar flow with drill string rotation provide better hole cleaning for different inclinations provided the drilling fluid has sufficient viscosity. Kendall's τ value indicates that apparent viscosity plays a more significant role in cleaning deviated wellbores compared to vertical and highly deviated wellbores for the current dataset.
- Drilling fluid flow rate influences the transport of heavier cuttings and larger cuttings more while RPM has higher influence on the transport of lighter cuttings and smaller cuttings.
- Better hole cleaning by heavier drilling fluids than that by lighter fluids. However, an increase in drilling fluid density results in a reduction of drilling rate for all inclinations (ref. The corresponding Kendall's τ values).

Asymmetry in data distribution for each of the 12 test parameters clearly indicates that nonparametric modeling method such as fuzzy logic (FL), a soft computational modeling method resembling human reasoning, can be used to model downhole cuttings concentration using the current experimental dataset. FL is used with success in different disciplines including Petroleum Engineering.

Credit author statement

Conceptualization, D.C; methodology, software, validation, formal analysis and writing—original draft preparation, D.C; writing—review and editing D.C, S.H and B.L; visualization D.C; Supervision, S.H and B. L. All authors have read and agreed to the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors are thankful to Sintef Industry (Drilling & Well) for sharing their experimental data for the current study.

Appendix

Table App 1
Summary of Experimental Dataset used

Experimenter (year)	Test Fluid	Annulus Size and Length (Inch and m)	Eccentricity (fraction)	Simulated ROP (m/hr)	RPM	Test Temperature (°C)	Pressure (bar)	Flow Rate (lpm)	Inclination (°)	Cuttings Size and Density (mm and kg/m^3)	Cuttings Packed Porosity (fraction)
Ahmed et al. (Ahmed et al., 2010; Sagheer, 2009) (2009) ¥: Email correspondence	Poly Anionic Cellulose (PAC) and water solution (PAC concentration: 149.8 g/l) Properties: Consistency index, K = 0.215 Pas^n Flow behavior index, n = 0.69 Density = 998 kg/m$^{3¥}$	4.5 × 8.0 3.5 × 8.0 3.0 × 8.0 25.9	+0.5$^¥$	12.2 18.3 24.4	90 110 140	27$^¥$	Ambient (1 bar)	1136 1514 2082	40 65 90	3.35 2600	0.4
Iyoho A. W. (Iyoho, 1980) (1980) ¥: Email correspondence	Carbopol-934 solution High viscosity bentonite solution Water Low viscosity bentonite solution Test fluid properties: Consistency index, K = 0.28, 0.45, 1 and 0.04 Pas^n Flow behavior index, n = 0.64, 0.61, 1 and 0.68 Density = 1012.5, 1018.5, 998.7 and 1006.5 kg/m^3	5 × 1.9 12.2	−0.5 0 +0.5	39.9 – 79.8	0 50 100	27$^¥$	Ambient (1 bar)	189.3 283.9 378.5 473.2 567.8 662.4	0–90	6.35 2651.3	–
Yu et al. (Yu et al., 2007) (2007) €: Assumed €¥: Assumed according to Ref. (Li and Luft, 2014a)	Poly Anionic Cellulose, Xanthan gum (XCD) and water solution. Poly Anionic Cellulose, Xanthan gum (XCD), Barite and water solution. Water Test fluid properties: Plastic viscosity, μ_p = 10, 20 and 1 cP Yield point, τ_y = 9.6, 19.2 and 0 Pa Density = 998, 1438 and 998 kg/m^3	5.76 × 3.5 17.5	0.48 0.78	4.6 6.1 9.1 12.2	0 80	27 49 82	138	284 379 568 757	90 67	3.35$^€$ 2650$^{€¥}$	–
Zhang F. (Zhang, 2015) (2015) ¥: Email correspondence	Water Test fluid properties: Consistency index, K = 1 Pas^n Flow behavior index, n = 1 Density = 999 kg/m^3 Apparent viscosity = 1 cP	8 × 4.5 27.4	1.0	13.7 29.0	0 100	27$^¥$	Ambient (1 bar)	757 1420 2078	30 45 50 55 60 90	3.0 2667	0.4
Ytrehus et al. (Ytrehus et al., 2021b) (2020)	Water-based mud (commercial field used mud) Oil-based mud (commercial field used mud) Test fluid properties: Consistency index, K = 1.302 (WBM) and 0.49612 (OBM) Pas^n Flow behavior index, n = 0.55048 (WBM) and 0.73643 (OBM) Yield point, τ_y = 0.6144 (WBM) and 0.6383 (OBM) Pa	3.94 × 1.98 10	0.5	8.0	0 10 20 30 50 100 150	28	Ambient (1 bar)	176.7 247.4 318.1 353.4 381.7 388.8	48 60 90	1.3 2632	–

(continued on next page)

Table App 1 (*continued*)

Experimenter (year)	Test Fluid	Annulus Size and Length (Inch and m)	Eccentricity (fraction)	Simulated ROP (m/hr)	RPM	Test Temperature (°C)	Pressure (bar)	Flow Rate (lpm)	Inclination (°)	Cuttings Size and Density (mm and kg/m^3)	Cuttings Packed Porosity (fraction)
	Average Density = 1642 (WBM) and 1610.1 (OBM) kg/m^3										
Ytrehus et al. (Ytrehus et al., 2020, 2021a) (2020)	Three oil-based mud of different viscosities (commercial field used mud) Test fluid properties: Consistency index, K = 0.0374, 0.1408 and 0.1387 Pas^n Flow behavior index, n = 0.88, 0.78 and 0.82 Yield point, τ_y = 0.196, 1.29 and 1.8 Pa Average Density = 1430, 1440 and 1490 kg/m^3	3.94 × 1.98 10	1.0	8.0	0 3 50 100 150	28	Ambient (1 bar)	176.7 247.4 251.4 318.1 323.2 388.8	48 60 90	1.3 2632	-

Note: The rheological properties of the test fluids together with the associated annulus dimensions and flow rates are used to calculate the corresponding apparent viscosity for each fluid. Formulations presented in (Bourgoyne et al., 1986) and (Maglione et al., 1996) are used to determine this parameter.

Table App 2
Strength categorization of correlation coefficient (Xiao et al., 2016)

Correlation coefficient	Strength categorization
−1.0 to −0.5 or 1.0 to 0.5	Strong
−0.5 to −0.3 or 0.3 to 0.5	Moderate
−0.3 to −0.1 or 0.1 to 0.3	Weak
−0.1 to 0.1	None or very weak

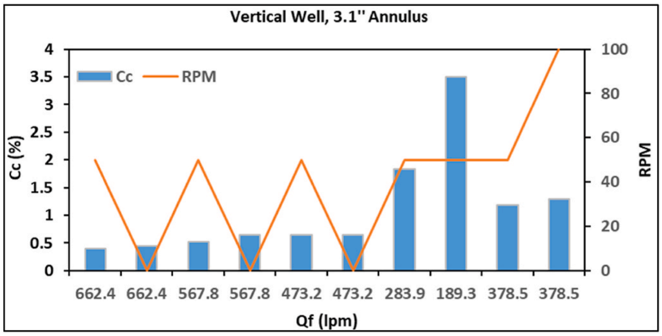


Fig. App. 1. Excerpt from data showing insignificant contribution of string rotation to cuttings transport in vertical wellbore

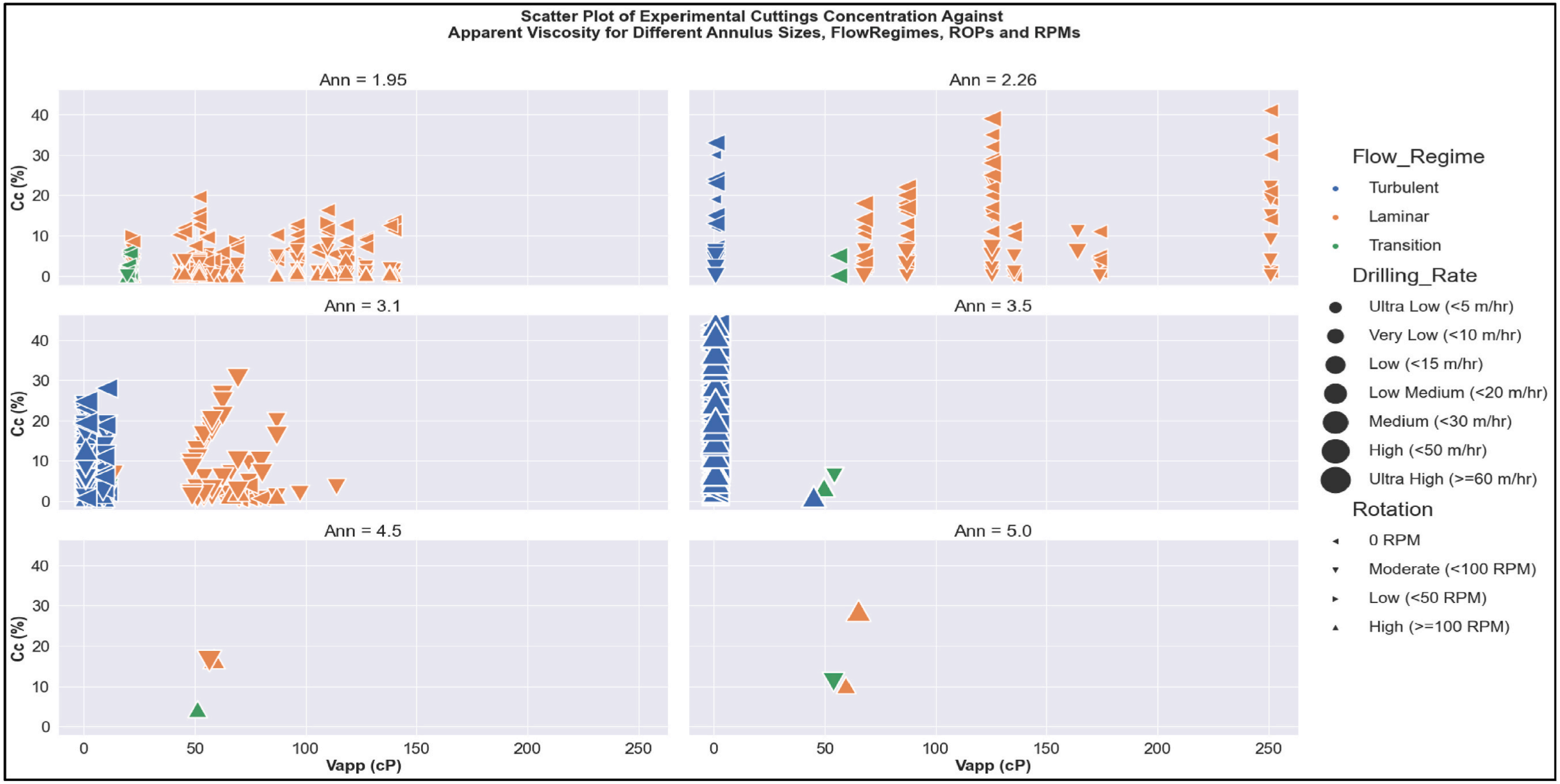
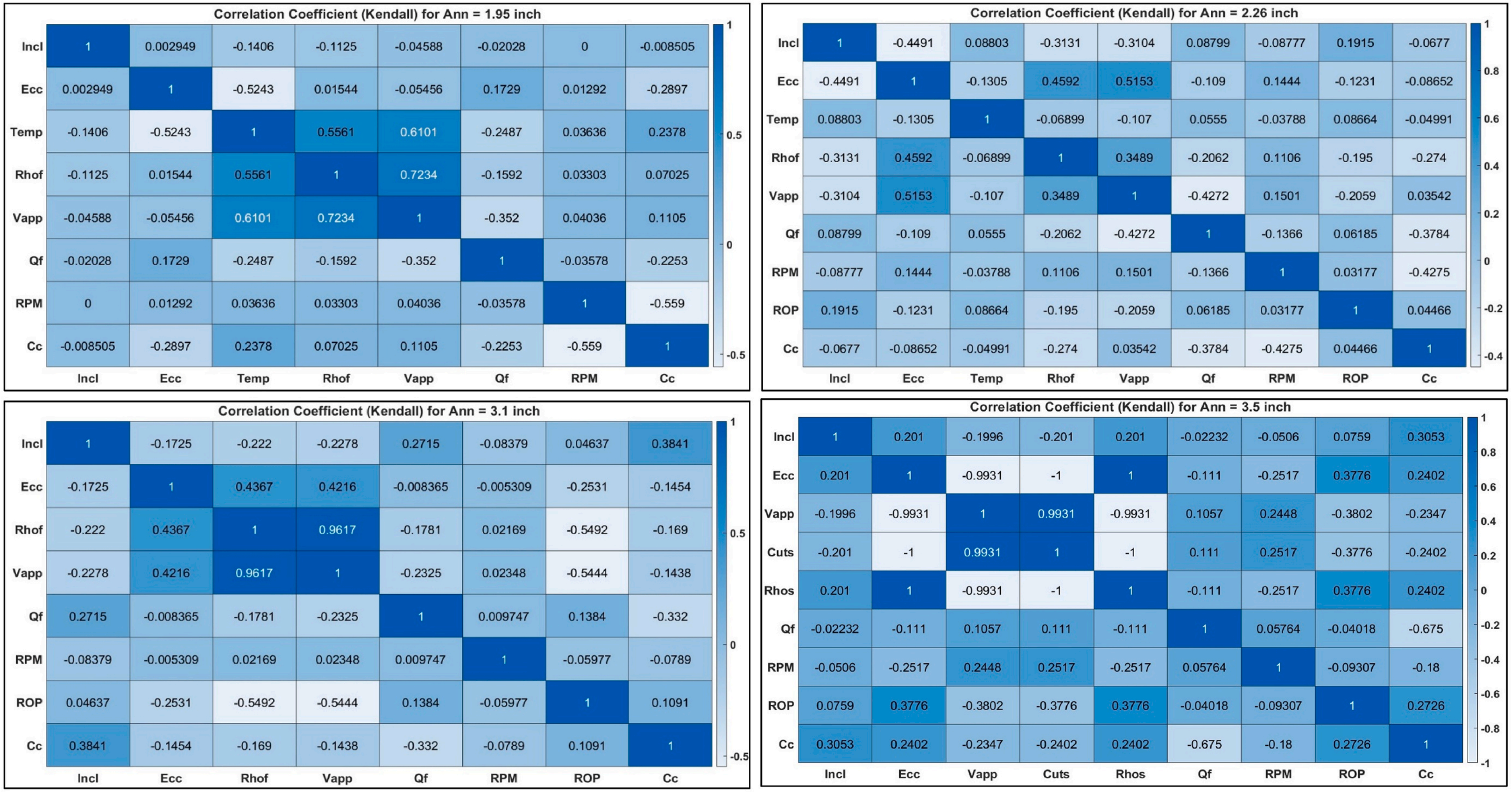


Fig. App. 2. 6D scatter plot showing changes in experimental Cc with apparent viscosity for different annulus sizes (subplots or facets) along with different flow regimes, ROPs and RPMs. Flow regimes are determined using Reynolds number (NRe). Flow regime is laminar if NRe <2000, turbulent if NRe >4000 and transition for 2000 ≤ NRe ≤4000.



Correlation Coefficient (Kendall) for Ann = 1.95 inch

	Incl	Ecc	Temp	Rhof	Vapp	Qf	RPM	Cc
Incl	1	0.002949	-0.1406	-0.1125	-0.04588	-0.02028	0	-0.008505
Ecc	0.002949	1	-0.5243	0.01544	-0.05456	0.1729	0.01292	-0.2897
Temp	-0.1406	-0.5243	1	0.5561	0.6101	-0.2487	0.03636	0.2378
Rhof	-0.1125	0.01544	0.5561	1	0.7234	-0.1592	0.03303	0.07025
Vapp	-0.04588	-0.05456	0.6101	0.7234	1	-0.352	0.04036	0.1105
Qf	-0.02028	0.1729	-0.2487	-0.1592	-0.352	1	-0.03578	-0.2253
RPM	0	0.01292	0.03636	0.03303	0.04036	-0.03578	1	-0.559
Cc	-0.008505	-0.2897	0.2378	0.07025	0.1105	-0.2253	-0.559	1

Correlation Coefficient (Kendall) for Ann = 2.26 inch

	Incl	Ecc	Temp	Rhof	Vapp	Qf	RPM	ROP	Cc
Incl	1	-0.4491	0.08803	-0.3131	-0.3104	0.08799	-0.08777	0.1915	-0.0677
Ecc	-0.4491	1	-0.1305	0.4592	0.5153	-0.109	0.1444	-0.1231	-0.08652
Temp	0.08803	-0.1305	1	-0.06899	-0.107	0.0555	-0.03788	0.08664	-0.04991
Rhof	-0.3131	0.4592	-0.06899	1	0.3489	-0.2062	0.1106	-0.195	-0.274
Vapp	-0.3104	0.5153	-0.107	0.3489	1	-0.4272	0.1501	-0.2059	0.03542
Qf	0.08799	-0.109	0.0555	-0.2062	-0.4272	1	-0.1366	0.06185	-0.3784
RPM	-0.08777	0.1444	-0.03788	0.1106	0.1501	-0.1366	1	0.03177	-0.4275
ROP	0.1915	-0.1231	0.08664	-0.195	-0.2059	0.06185	0.03177	1	0.04466
Cc	-0.0677	-0.08652	-0.04991	-0.274	0.03542	-0.3784	-0.4275	0.04466	1

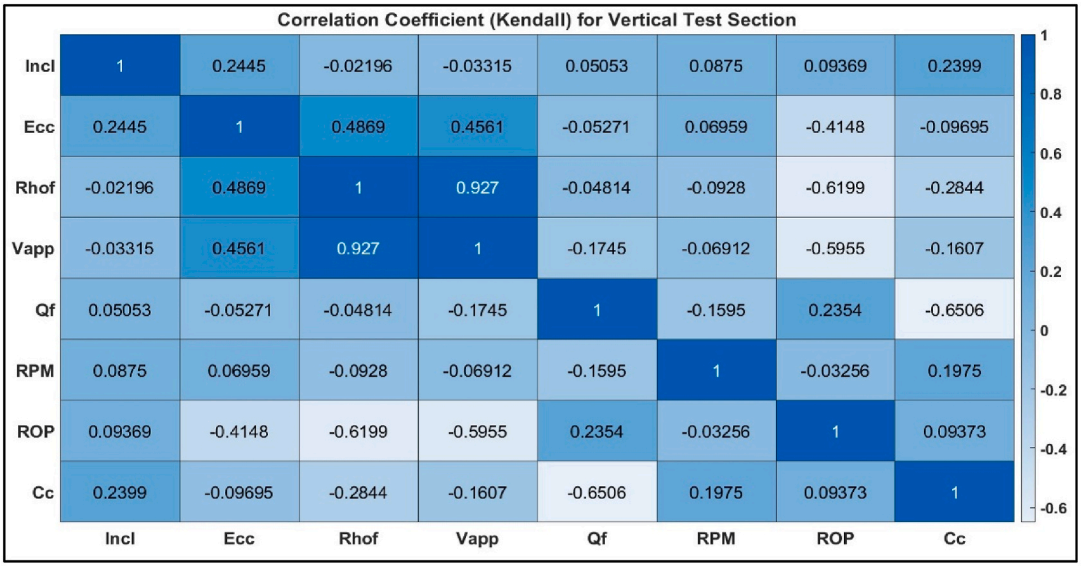
Correlation Coefficient (Kendall) for Ann = 3.1 inch

	Incl	Ecc	Rhof	Vapp	Qf	RPM	ROP	Cc
Incl	1	-0.1725	-0.222	-0.2278	0.2715	-0.08379	0.04637	0.3841
Ecc	-0.1725	1	0.4367	0.4216	-0.008365	-0.005309	-0.2531	-0.1454
Rhof	-0.222	0.4367	1	0.9617	-0.1781	0.02169	-0.5492	-0.169
Vapp	-0.2278	0.4216	0.9617	1	-0.2325	0.02348	-0.5444	-0.1438
Qf	0.2715	-0.008365	-0.1781	-0.2325	1	0.009747	0.1384	-0.332
RPM	-0.08379	-0.005309	0.02169	0.02348	0.009747	1	-0.05977	-0.0789
ROP	0.04637	-0.2531	-0.5492	-0.5444	0.1384	-0.05977	1	0.1091
Cc	0.3841	-0.1454	-0.169	-0.1438	-0.332	-0.0789	0.1091	1

Correlation Coefficient (Kendall) for Ann = 3.5 inch

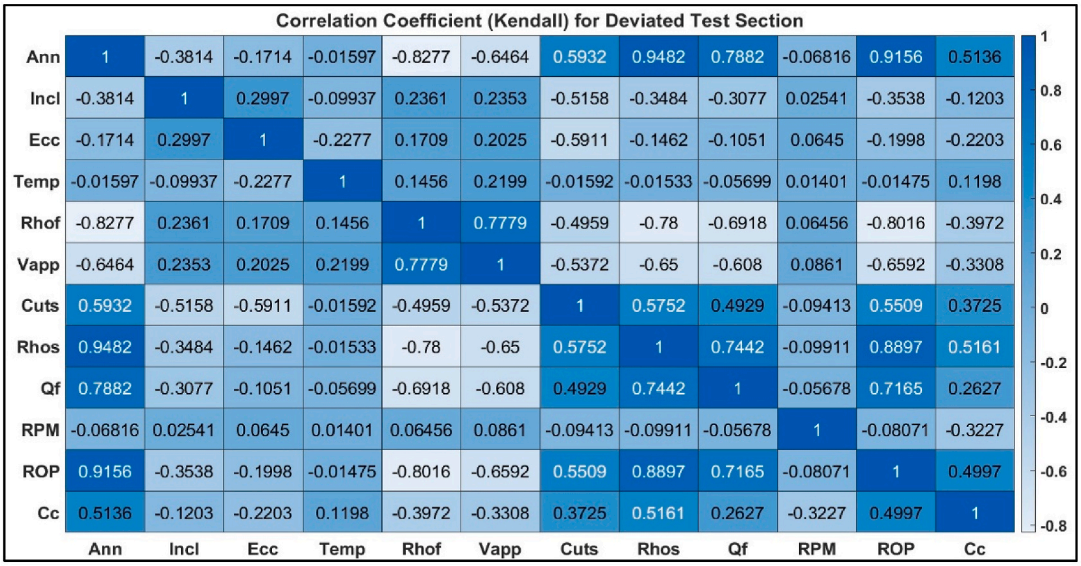
	Incl	Ecc	Vapp	Cuts	Rhos	Qf	RPM	ROP	Cc
Incl	1	0.201	-0.1996	-0.201	0.201	-0.02232	-0.0506	0.0759	0.3053
Ecc	0.201	1	-0.9931	-1	1	-0.111	-0.2517	0.3776	0.2402
Vapp	-0.1996	-0.9931	1	0.9931	-0.9931	0.1057	0.2448	-0.3802	-0.2347
Cuts	-0.201	-1	0.9931	1	-1	0.111	0.2517	-0.3776	-0.2402
Rhos	0.201	1	-0.9931	-1	1	-0.111	-0.2517	0.3776	0.2402
Qf	-0.02232	-0.111	0.1057	0.111	-0.111	1	0.05764	-0.04018	-0.675
RPM	-0.0506	-0.2517	0.2448	0.2517	-0.2517	0.05764	1	-0.09307	-0.18
ROP	0.0759	0.3776	-0.3802	-0.3776	0.3776	-0.04018	-0.09307	1	0.2726
Cc	0.3053	0.2402	-0.2347	-0.2402	0.2402	-0.675	-0.18	0.2726	1

Fig. App. 3. Kendall's τ for different annulus sizes



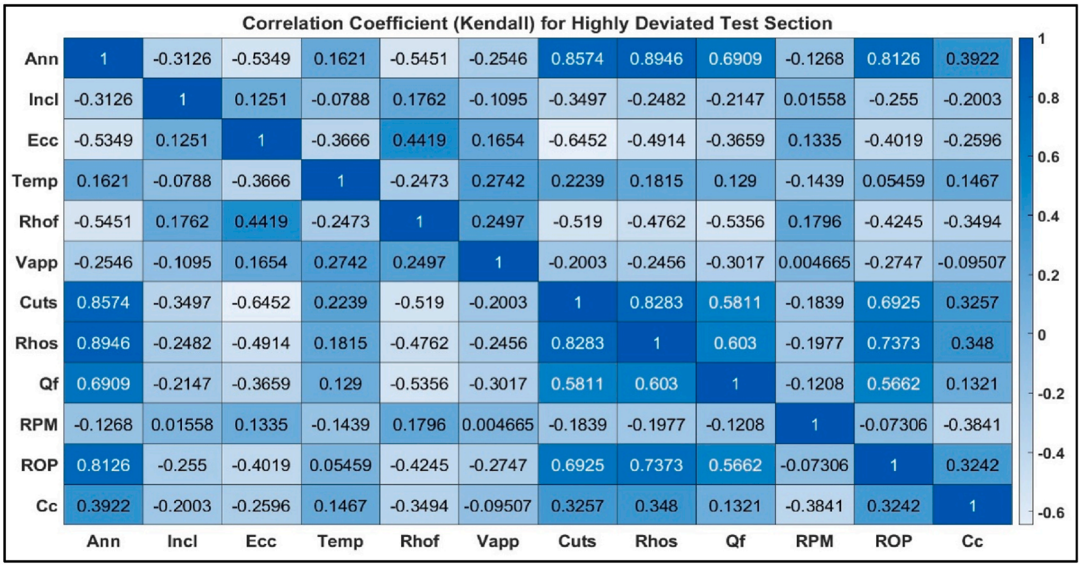
Correlation Coefficient (Kendall) for Vertical Test Section

	Incl	Ecc	Rhof	Vapp	Qf	RPM	ROP	Cc
Incl	1	0.2445	-0.02196	-0.03315	0.05053	0.0875	0.09369	0.2399
Ecc	0.2445	1	0.4869	0.4561	-0.05271	0.06959	-0.4148	-0.09695
Rhof	-0.02196	0.4869	1	0.927	-0.04814	-0.0928	-0.6199	-0.2844
Vapp	-0.03315	0.4561	0.927	1	-0.1745	-0.06912	-0.5955	-0.1607
Qf	0.05053	-0.05271	-0.04814	-0.1745	1	-0.1595	0.2354	-0.6506
RPM	0.0875	0.06959	-0.0928	-0.06912	-0.1595	1	-0.03256	0.1975
ROP	0.09369	-0.4148	-0.6199	-0.5955	0.2354	-0.03256	1	0.09373
Cc	0.2399	-0.09695	-0.2844	-0.1607	-0.6506	0.1975	0.09373	1



Correlation Coefficient (Kendall) for Deviated Test Section

	Ann	Incl	Ecc	Temp	Rhof	Vapp	Cuts	Rhos	Qf	RPM	ROP	Cc
Ann	1	-0.3814	-0.1714	-0.01597	-0.8277	-0.6464	0.5932	0.9482	0.7882	-0.06816	0.9156	0.5136
Incl	-0.3814	1	0.2997	-0.09937	0.2361	0.2353	-0.5158	-0.3484	-0.3077	0.02541	-0.3538	-0.1203
Ecc	-0.1714	0.2997	1	-0.2277	0.1709	0.2025	-0.5911	-0.1462	-0.1051	0.0645	-0.1998	-0.2203
Temp	-0.01597	-0.09937	-0.2277	1	0.1456	0.2199	-0.01592	-0.01533	-0.05699	0.01401	-0.01475	0.1198
Rhof	-0.8277	0.2361	0.1709	0.1456	1	0.7779	-0.4959	-0.78	-0.6918	0.06456	-0.8016	-0.3972
Vapp	-0.6464	0.2353	0.2025	0.2199	0.7779	1	-0.5372	-0.65	-0.608	0.0861	-0.6592	-0.3308
Cuts	0.5932	-0.5158	-0.5911	-0.01592	-0.4959	-0.5372	1	0.5752	0.4929	-0.09413	0.5509	0.3725
Rhos	0.9482	-0.3484	-0.1462	-0.01533	-0.78	-0.65	0.5752	1	0.7442	-0.09911	0.8897	0.5161
Qf	0.7882	-0.3077	-0.1051	-0.05699	-0.6918	-0.608	0.4929	0.7442	1	-0.05678	0.7165	0.2627
RPM	-0.06816	0.02541	0.0645	0.01401	0.06456	0.0861	-0.09413	-0.09911	-0.05678	1	-0.08071	-0.3227
ROP	0.9156	-0.3538	-0.1998	-0.01475	-0.8016	-0.6592	0.5509	0.8897	0.7165	-0.08071	1	0.4997
Cc	0.5136	-0.1203	-0.2203	0.1198	-0.3972	-0.3308	0.3725	0.5161	0.2627	-0.3227	0.4997	1



Correlation Coefficient (Kendall) for Highly Deviated Test Section

	Ann	Incl	Ecc	Temp	Rhof	Vapp	Cuts	Rhos	Qf	RPM	ROP	Cc
Ann	1	-0.3126	-0.5349	0.1621	-0.5451	-0.2546	0.8574	0.8946	0.6909	-0.1268	0.8126	0.3922
Incl	-0.3126	1	0.1251	-0.0788	0.1762	-0.1095	-0.3497	-0.2482	-0.2147	0.01558	-0.255	-0.2003
Ecc	-0.5349	0.1251	1	-0.3666	0.4419	0.1654	-0.6452	-0.4914	-0.3659	0.1335	-0.4019	-0.2596
Temp	0.1621	-0.0788	-0.3666	1	-0.2473	0.2742	0.2239	0.1815	0.129	-0.1439	0.05459	0.1467
Rhof	-0.5451	0.1762	0.4419	-0.2473	1	0.2497	-0.519	-0.4762	-0.5356	0.1796	-0.4245	-0.3494
Vapp	-0.2546	-0.1095	0.1654	0.2742	0.2497	1	-0.2003	-0.2456	-0.3017	0.004665	-0.2747	-0.09507
Cuts	0.8574	-0.3497	-0.6452	0.2239	-0.519	-0.2003	1	0.8283	0.5811	-0.1839	0.6925	0.3257
Rhos	0.8946	-0.2482	-0.4914	0.1815	-0.4762	-0.2456	0.8283	1	0.603	-0.1977	0.7373	0.348
Qf	0.6909	-0.2147	-0.3659	0.129	-0.5356	-0.3017	0.5811	0.603	1	-0.1208	0.5662	0.1321
RPM	-0.1268	0.01558	0.1335	-0.1439	0.1796	0.004665	-0.1839	-0.1977	-0.1208	1	-0.07306	-0.3841
ROP	0.8126	-0.255	-0.4019	0.05459	-0.4245	-0.2747	0.6925	0.7373	0.5662	-0.07306	1	0.3242
Cc	0.3922	-0.2003	-0.2596	0.1467	-0.3494	-0.09507	0.3257	0.348	0.1321	-0.3841	0.3242	1

Fig. App. 4. Kendall's τ for different inclinations

References

Abbas, A.K., Alsaba, M.T., Al Dushaishi, M.F., 2022. Comprehensive experimental investigation of hole cleaning performance in horizontal wells including the effects of drill string eccentricity, pipe rotation, and cuttings size. J. Energy Resour. Technol. 144 (6).

Adari, R.B., Miska, S., Kuru, E., Bern, P., Saasen, A., 2000. Selecting drilling fluid properties and flow rates for effective hole cleaning in high-angle and horizontal wells. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Ahmed, R.M., et al., 2010. Experimental studies on the effect of mechanical cleaning devices on annular cuttings concentration and applications for optimizing ERD systems. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Al-Rubaii, M.M., Gajbhiye, R.N., Al-Yami, A., Alshalan, M., Al-Awami, M.B., 2020. Automated evaluation of hole cleaning efficiency while drilling improves rate of penetration. In: International Petroleum Technology Conference. OnePetro.

Alkinani, H.H., Al-Hameedi, A.T., Dunn-Norman, S., Al-Alwani, M.A., Lian, D., Al-Bazzaz, W.H., 2019. Application of descriptive data analytics: how to properly select the best ranges of viscosity and flow rate for optimal hole cleaning?. In: SPE Eastern Regional Meeting. OnePetro.

Azar, J., Sanchez, R.A., 1997. Important issues in cuttings transport for drilling directional wells. In: Latin American and Caribbean Petroleum Engineering Conference. Society of Petroleum Engineers.

Badrouchi, F., 2021. Hole Cleaning and Cuttings Transportation Modelling and Optimization. The University of North Dakota.

Becker, T., Azar, J., Okrajni, S., 1991. Correlations of mud rheological properties with cuttings-transport performance in directional drilling. SPE Drill. Eng. 6 (1), 16–24.

Berk, M., 2021. How to use Permutation Tests - a walkthrough of permutation tests and how they can be applied to time series data, 21/09 [Online]. Available: https://towardsdatascience.com/how-to-use-permutation-tests-bacc79f45749.

Bhandari, P., 2021. Correlation Coefficient | Types, Formulas & Examples, 02/12 [Online]. Available:

Bilgesu, H.I., Mishra, N., Ameri, S., 2007. Understanding the effect of drilling parameters on hole cleaning in horizontal and deviated wellbores using computational fluid dynamics. In: Eastern Regional Meeting. OnePetro.

Bourgoyne, A.T., Millheim, K.K., Chenevert, M.E., Young, F.S., 1986. Applied Drilling Engineering. Society of Petroleum Engineers Richardson.

Campos, W., 1995. Mechanistic Modeling of Cuttings Transport in Directional Wells. The University of Tulsa.

Cayeux, E., Mesagan, T., Tanripada, S., Zidan, M., Fjelde, K.K., 2014. Real-time evaluation of hole-cleaning conditions with a transient cuttings-transport model. SPE Drill. Complet. 29 (1), 5–21.

Chok, N.S., 2010. Pearson's versus Spearman's and Kendall's Correlation Coefficients for Continuous Data. University of Pittsburgh.

Chowdhury, D., Hovda, S., 2022. Estimation of downhole cuttings concentration from experimental data–comparison of empirical and fuzzy logic models. J. Petrol. Sci. Eng. 209, 109910.

Croux, C., Dehon, C., 2010. Influence functions of the Spearman and Kendall correlation measures. Stat. Methods Appl. 19 (4), 497–515.

Dan, A., 2020. Kurtosis( ) & skew( ). In: Function in Pandas, vol. 2022. https://medium.com/.

Deshmukh, V., Dewangan, S.K., 2022. Review on various borehole cleaning parameters related to oil and gas well drilling. J. Braz. Soc. Mech. Sci. Eng. 44 (5), 1–24.

Duan, M., Miska, S.Z., Yu, M., Takach, N.E., Ahmed, R.M., Zettner, C.M., 2006. Transport of small cuttings in extended reach drilling. In: International Oil & Gas Conference and Exhibition in China. Society of Petroleum Engineers.

Fjar, E., Holt, R.M., Raaen, A., Horsrud, P., 2008. Petroleum Related Rock Mechanics. Elsevier.

Flumignan, D., Anaia, G., de O Ferreira, F., Tininis, A., de Oliveira, J., 2007. Screening brazilian automotive gasoline quality through quantification of saturated hydrocarbons and anhydrous ethanol by gas chromatography and exploratory data analysis. Chromatographia 65 (9), 617–623.

Gavignet, A.A., Sobey, I.J., 1989. Model aids cuttings transport prediction. J. Petrol. Technol. 41 (9), 916–921.

Huque, M.M., Butt, S., Zendehboudi, S., Imtiaz, S., 2020a. Systematic sensitivity analysis of cuttings transport in drilling operation using computational fluid dynamics approach. J. Nat. Gas Sci. Eng. 81, 103386.

Huque, M.M., Imtiaz, S., Zendehboudi, S., Butt, S., Rahman, M.A., Maheshwari, P., 2020b. Experimental study of cuttings transport with non-Newtonian fluid in an inclined well using visualization and ERT techniques. D022S061R009. In: SPE Annual Technical Conference and Exhibition. https://doi.org/10.2118/201709-ms [Online]. Available: (Accessed 27 October 2020).

Huque, M.M., Rahman, M.A., Zendehboudi, S., Butt, S., Imtiaz, S., 2022. Experimental and numerical study of cuttings transport in inclined drilling operations. J. Petrol. Sci. Eng. 208, 109394.

Iyoho, A.W.i., 1980. Drilling-Cutting Transport by Non-newtonian Drilling Fluids through Inclined, Eccentric Annuli. The University of Tulsa, PhD.

Jansen, F., Kelkar, M., 1996. Exploratory data analysis of production data. In: Permian Basin Oil and Gas Recovery Conference. OnePetro.

Kumar, M., Kumar, A., Palaparthy, V.S., 2020. Soil sensors-based prediction system for plant diseases using exploratory data analysis and machine learning. IEEE Sensor. J. 21 (16), 17455–17468.

Kürzl, H., 1988. Exploratory data analysis: recent advances for the interpretation of geochemical data. J. Geochem. Explor. 30 (1–3), 309–322.

Larsen, T., Pilehvari, A., Azar, J., 1997. Development of a new cuttings-transport model for high-angle wellbores including horizontal wells. SPE Drill. Complet. 12 (2), 129–136.

Li, J., Luft, B., 2014a. Overview of solids transport studies and applications in oil and gas industry-experimental work (Russian). In: SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition. Society of Petroleum Engineers.

Li, J., Luft, B., 2014b. Overview solids transport study and application in oil-gas industry-theoretical work. In: International Petroleum Technology Conference. International Petroleum Technology Conference.

Li, J., Walker, S., 1999. Sensitivity analysis of hole cleaning parameters in directional wells. All Days, SPE-54498-MS. In: SPE/ICoTA Coiled Tubing Roundtable. https://doi.org/10.2118/54498-ms [Online]. Available:

Li, Y., Bjorndalen, N., Kuru, E., 2004. Numerical modelling of cuttings transport in horizontal wells using conventional drilling fluids. In: Canadian International Petroleum Conference. Petroleum Society of Canada.

Maglione, R., Gallino, G., Robotti, G., Romagnoli, R., Rommetveit, R., 1996. A drilling well as viscometer: studying the effects of well pressure and temperature on the rheology of the drilling fluids. In: European Petroleum Conference. OnePetro.

Martinez, W.L., Martinez, A.R., 2001. Computational Statistics Handbook with MATLAB. Chapman and Hall/CRC.

Martinez, W.L., Martinez, A.R., Solka, J.L., 2017. Exploratory Data Analysis with MATLAB®. Chapman and Hall/CRC.

Mitchell, R.F., 2006. Drilling Engineering. In: Petroleum Engineering Handbook), vol. 2. Soc. of Petroleum Engineers.

Nazari, T., Hareland, G., Azar, J.J., 2010. Review of cuttings transport in directional well drilling: systematic approach. In: SPE Western Regional Meeting. Society of Petroleum Engineers.

Ogunrinde, J., Dosunmu, A., 2012. Hydraulics optimization for efficient hole cleaning in deviated and horizontal wells. In: Nigeria Annual International Conference and Exhibition. OnePetro.

Ogunsina, K., Bilionis, I., DeLaurentis, D., 2021. Exploratory data analysis for airline disruption management. Machine Learning with Applications 6, 100102.

Okrajni, S., Azar, J., 1986. The effects of mud rheology on annular hole cleaning in directional wells. SPE Drill. Eng. 1 (4), 297–308.

Ozbayoglu, M.E., Saasen, A., Sorgun, M., Svanes, K., 2008. Effect of pipe rotation on hole cleaning for water-based drilling fluids in horizontal and deviated wells. In: IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. Society of Petroleum Engineers.

Peden, J.M., Ford, J.T., Oyeneyin, M.B., 1990. Comprehensive experimental investigation of drilled cuttings transport in inclined wells including the effects of rotation and eccentricity. In: European Petroleum Conference, All Days. SPE-20925-MS. https://doi.org/10.2118/20925-ms [Online]. Available:

Pilehvari, A.A., Azar, J., Shirazi, S.A., 1999. State-of-the-art cuttings transport in horizontal wellbores. SPE Drill. Complet. 14 (3), 196–200.

Popovich, P.Y.C.P.M., 2002. Correlation. Thousand Oaks, California [Online]. Available: https://methods.sagepub.com/book/correlation. Accessed on: 02/01/2022.

Qahtani, A.M., Amanullah, M., 2010. Prediction of hole cleaning efficiency using a simple, user friendly and better performing simulation model. In: SPE/DGS Saudi Arabia Section Technical Symposium and Exhibition. Society of Petroleum Engineers.

Rabia, H., 1989. Rig Hydraulics. Entrac Software, Newcastle Upon Tyne, England, p. 249 (in English).

Rasool Khosravanian, B.S.A., 2022. Methods for Petroleum Well Optimization. Gulf Professional Publishing.

Ravi, K., Hemphill, T., 2006. Pipe rotation and hole cleaning in eccentric annulus. In: IADC/SPE Drilling Conference. Society of Petroleum Engineers.

Reda, M., El Sayed, N., Shalaby, S., Farahat, M., 2018. A statistical model for hole cleaning and cuttings transport efficiency during drilling of wells. Journal of Petroleum and Mining Engineering 20 (1), 30–40.

Rooney. Correlation (Pearson, spearman, and Kendall) [Online]. Available: https://www.kaggle.com/kiyoung1027/correlation-pearson-spearman-and-kendall/report?scriptVersionId=25999032.

Rousseeuw, P.J., Hubert, M., 2018. Anomaly detection by robust statistics. Wiley Interdisciplinary Reviews: Data Min. Knowl. Discov. 8 (2), e1236.

Saasen, A., 1998. Hole cleaning during deviated drilling-The effects of pump rate and rheology. In: European Petroleum Conference. Society of Petroleum Engineers.

Sagheer, M., 2009. Study of Effect of Down-Hole Mechanical Cleaning Devices (MCDs) on Cuttings Transport. MSc, The University of Tulsa.

Sayindla, S., 2018. Study of Cuttings Transport Using Water-Based and Oil-Based Drilling Fluids," PhD. Norwegian University of Science and Technology.

Sifferman, T., Becker, T., 1992. Hole cleaning in full-scale inclined wellbores. SPE Drill. Eng. 7 (2), 115–120.

Sorgun, M., 2010. Modeling of Newtonian Fluids and Cuttings Transport Analysis in High Inclination Wellbores with Pipe Rotation.

Swamynathan, M., 2019. Mastering Machine Learning with python in Six Steps: A Practical Implementation Guide to Predictive Data Analytics Using python. Apress.

Tomren, P.H., Iyoho, A.W., Azar, J.J., 1986. Experimental study of cuttings transport in directional wells. SPE Drill. Eng. 1 (1), 43–56. https://doi.org/10.2118/12123-pa.

Werner, B., 2018. PhD. In: The Influence of Drilling-Fluid Rheology on Cuttings-Bed Behavior. Norwegian University of Science and Technology.

Xiang, Y., Liu, G., Vertex, P., 2012. Impact of cuttings concentration on ECD during drilling. In: AADE Fluids Tech. Conf. Exhib.

Xiao, C., Ye, J., Esteves, R.M., Rong, C., 2016. Using Spearman's correlation coefficients for exploratory data analysis on big dataset. Concurrency Comput. Pract. Ex. 28 (14), 3866–3878.

Ytrehus, J.D., et al., 2018. Cuttings bed removal in deviated wells. V008T11A065. In: Offshore and Arctic Engineering ASME 2018 37th International Conference on Ocean, ume 8. Petroleum Technology. https://doi.org/10.1115/omae2018-77832 [Online]. Available:Polar and Arctic Sciences and Technology.

Ytrehus, J.D., Lund, B., Taghipour, A., Carazza, L., Gyland, K.R., Saasen, A., 2020. Drilling fluid's cuttings bed removal properties for deviated wellbores. In: International Conference on Offshore Mechanics and Arctic Engineering, vol. 84430. American Society of Mechanical Engineers. V011T11A065.

Ytrehus, J.D., Lund, B., Taghipour, A., Carazza, L., Gyland, K.R., Saasen, A., 2021a. Oil-based drilling fluid's cuttings bed removal properties for deviated wellbores. J. Energy Resour. Technol. 143 (10), 103003.

Ytrehus, J.D., Lund, B., Taghipour, A., Saasen, A., 2021b. Cuttings transport with oil- and water-based drilling fluids. In: International Conference on Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers.

Yu, M., Takach, N.E., Nakamura, D.R., Shariff, M.M., 2007. An experimental study of hole cleaning under simulated downhole conditions. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Zhang, F., 2015. Numerical Simulation and Experimental Study of Cuttings Transport in Intermediate Inclined Wells," PhD. The University of Tulsa.