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A review of technological advances and open challenges for oil and gas drilling systems engineering

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Abstract

The ever-increasing quest to identify, secure, access and operate oil and gas fields is continuously expanding to the far corners of the planet, facing extreme conditions towards exploring, securing and deriving maximum fluid benefits from established and unconventional fossil fuel sources alike: to this end, the unprecedented geological, climatic, technical and operational challenges have necessitated the development of revolutionary drilling and production methods. This review paper focuses on a technological field of great importance and formidable technical complexity - that of well drilling for fossil fuel production. A vastly expanding body of literature addresses design and operation problems with remarkable success: what is even more interesting is that many recent contributions rely on multidisciplinary approaches and reusable Process Systems Engineering (PSE) methodologies - a drastic departure from ad hoc/one-use tools and methods of the past.

The specific goals of this review are to first, review the state of art in active fields within drilling engineering, and explore currently pressing technical problems, which are in dire need, or have recently found, PSE-and/or CFD-relevant solutions. Then, we illustrate the methodological versatility of novel PSE-based approaches for optimization and control, with an emphasis on contemporary problems. Finally, we highlight current challenges and opportunities for truly innovative research contributions, which require the combination of best-in-class methodological and software elements in order to deliver applicable solutions of industrial importance.

1.0 Well drilling in the oil and gas industry

The annual increase in global energy demand and the diverse applications of conventional & unconventional oil and gas resources are indicative of the fact that these resources will continuously remain relevant to humanity in the far future. With increasing climate change concerns, natural gas already provides a promising transition between some oil-based fuels and renewables in the long run, despite its well-known transportation difficulties.[1] It can be further argued that natural gas represents an economically attractive option for electricity generation (particularly in the US where shale gas is naturally abundant) with significantly reduced greenhouse gas emissions compared to coal; thus increasing its market demand.[2] These reasons have warranted the advancements in technologies of varying sophistication for larger-scale development of complex hydrocarbon reservoirs, over the past ten decades. Oil field development projects aim to locate, characterise and extract oil and gas resources in a safe and profitable way over the field's lifetime. These processes can be systematically classified into the exploration (searching for oil and gas deposits), appraisal (investigating the volume of reserves), development (install oilrig & processing equipment), production (fluid extraction) and abandonment (uninstalling facilities) phases.[3]

It can be argued that well drilling is the most important activity that takes place throughout a field's life and it spans through the appraisal to the production phases. Only by drilling a well, can a well prospect be validated after many geological and geophysical (seismic-based) interpretations in the exploration phase. It is not surprising that a derrick (Fig. 1) towering high above the well site has become the most recognisable icon of the oil and gas industry. The drilling process commences with a plan of a well trajectory that optimises the wellbore's exposure to the pay zones of a reservoir/formation; subsequently, designs of the bottomhole assemblies to attain the desired trajectory are made. The surface location, total vertical depth (TVD), measured depth (MD), bit and drill pipe size, casing size, mud weights, extent of drill pipe's rotating and reciprocating motion, kick-off point (KOP) and well azimuth are some important variables that characterize the drilling process and its resultant cost as stated in an authorization for expenditure.[4]

The average capital cost of constructing a well (drilling, completion and facilities) in US onshore basins could be as high as \$8.3 million. Drilling alone translates to approximately 31% of the total well development costs.[5] In 2015, Shell abandoned drilling activities in the Arctic (northwest coast of Alaska – \$7 billion USD worth of investment) after finding disappointing results from a well in Chukchi Sea. Huge drilling and developing costs of the project were some of the main reasons leading to such decision.[6,7] This example demonstrates the challenges of field development in difficult-to-access, environmentally unfriendly and highly uncertain regions, which oil companies must address to maintain global relevance. Typically, oil fields may consist of tens to hundreds of wells depending on their size. Thus, operating companies pay detailed attention to reducing total drilling time and the corresponding well cost. This cost involvement is one of the major reasons why major oil companies form partnerships (joint ventures) to share the development costs.

The complicated economics, technical operational challenges and the overall multifaceted nature of industrial drilling activities have made it open to multiscale modelling, robust simulation methodologies and state of the art experimentation techniques for accurate understanding of the flow scenarios and optimal parameters necessary for a problem-free operation.[8–10] Over the past decades, the field has attracted numerous successful contributions from the chemical, petroleum and mechanical engineering communities for well trajectory optimisation and particle removal/hole cleaning processes. More recently, a body of literature specifically belonging to the process systems engineering community has emerged; majorly targeting wellbore stability challenges with respect to the fracture pressure and pore pressure.[11–14] In light of these contributions, this paper aims to:

Figure 1: Components of a typical drilling system.[15]

- Review the state of art in active fields within drilling engineering, and explore currently pressing technical problems, which are in dire need, or have recently found, PSE-and/or CFD-relevant solutions, e.g. wellbore pressure control cuttings transport, multiphase operational protocols and drilling fluid rheology modeling and optimization.
- Illustrate the methodological versatility of novel PSE-based approaches for optimization and control, with an emphasis on contemporary problems, e.g. underbalanced/UBD and managed pressure/MPD drilling model identification, optimization and control, and their variations.
- Highlight factors limiting the industrial application of the developed numerical methods and experimental findings with recommendations, which could aid their applicability; thus opening a new area of research for improved experiments and simulations.
- Highlight current challenges and opportunities for truly innovative research contributions, which require the combination of best-in-class methodological and software elements in order to deliver applicable solutions of industrial importance.

Before presenting detailed discussions on the advancements in drilling systems engineering, we briefly describe some of the drilling terminology that are used in subsequent sections of the text for better comprehension and clarity. These definitions are adapted from the Schlumberger Oilfield Glossary.

- **Wellbore/borehole:** the drilled hole or the space between the rock face and the drillpipe.
- **Cuttings:** particles generated because of the cutting action of the drill bit on the rock formation.
- **Drillstring:** the combination of the drill pipes used to make the drill bit turn at the bottom of the wellbore.
- **Fishing:** the application of techniques for the removal of objects (debris, tools etc.) left in the wellbore during drilling operations.
- **Kick:** the flow of formation fluids into the wellbore during drilling operations.
- **Kick detection:** the use of sensors and flow devices to determine the influx of formation fluids from the rock formation to the wellbore.
- **Kick attenuation:** the reduction in the influx rate of fluids from the formation to the wellbore.
- **Kick-off point:** the point at which a vertical well is intentionally deviated.
- **Logging While Drilling:** the process of measuring rock formation properties simultaneously as drilling progresses.
- **Measured Depth:** the length of a wellbore as if determined using a measuring stick.
- **True Vertical Depth:** the vertical distance from a point in the well (usually the current or final depth) to a point at the surface.

- **Rate of Penetration:** the speed at which the drill bit breaks a rock formation, thus deepening the wellbore.
- **Weight on Bit:** the amount of downward force exerted on the drill bit.

2.0 Challenges of drilling operations and real field drilling case studies

Excessive drill pipe torque, slow drilling rates, pressure instabilities, stuck drill pipe and loss circulation are some of the operational challenges faced by drilling engineers.[16,17] These problems culminate to an increased overall cost, reduced efficiency of the drilling process, unwanted fluid influx, severe interruption for days and sometimes an entire abandonment of the well. In the following section, a detailed discussion of these problems is presented with some real field observations.

2.1 Flow assurance & hydrate bearing zones

Flow assurance evaluates the potential of hydrocarbons to disrupt field operations due to deposition and instabilities in a flow system.[18] This problem is mostly thought to be production-related; however, flow assurance difficulties also arise during drilling operations. The increase in the number of deep-water drilling operations and the move towards environmentally friendly water-based over oil-based drilling muds have resulted in frequent hydrate-related problems over the past decade. Hydrates are crystalline solids formed by the encasement of gas molecules in cages of water molecules.[19] These solids may also occur during underbalanced drilling (UBD) operations in which there is deliberate maintenance of the wellbore pressure below the formation pressure. Although UBD technology enhances penetration rates and reduces the risk of invasive formation damage, this pressure difference created induces a net influx of fluids from the reservoir into the wellbore as drilling progresses. These fluids are circulated back to the surface together with the mud and cuttings. In gas-bearing reservoirs, there is potential for hydrate formation at the right conditions of falling temperature and high pressures; this could plug the wellbore, subsea risers, chokes and blowout preventers - BOPs.[20] Furthermore, hydrate bearing zones and sediments are occasionally encountered during operations.[20–22] If this is the case, gas hydrate dissociation occurs, and gas released will erode the drilling pipe, thus increasing the risk of mechanical failure. In addition to this risk, the mud density is reduced and there could be uncontrolled flow (potentially leak to the sea floor) and ultimately a blowout of the well.[23]

A comprehensive geotechnical investigation was carried out by Shell to evaluate the potential of drilling difficulties due to gas hydrates in the Gumusut-Kakap offshore development in Malaysia.[24] This was done using logging while drilling (LWD) techniques coupled with rigorous seismic interpretations. The presence of hydrates was observed from the abnormal LWD responses and the gas bubbles produced at the wellhead during drillpipe connections. Numerical simulations were carried out to evaluate in more detail the implication of gas hydrates on the sustainability of the field’s development. The results implied a change in location in the location of the development wells, although at a significant expense.

These hydrate-related problems have continued to draw much research attention over the years, especially from a mathematical modeling point of view (for thermodynamic prediction of hydrate formation and dissociation conditions, equivalent density and viscosity determination of gas-mud mixtures and pressure-rate predictions). This is because of the high explosion risks involved with handling natural gas and its hydrate equivalent under laboratory conditions. These numerical advancements are however plagued by the fact that typical rate relationships are usually highly nonlinear; this creates a difficulty in ascertaining what pump pressures are required to initiate a desired flowrate in a wellbore. This complication is further augmented by the fact that non-Newtonian flows are challenging from an analysis perspective.[25] Only few exact solutions are available for circular pipe/annular cross sections. However, when realistic operational difficulties like a heavily clogged eccentric wellbores exist, the flow geometry becomes non-circular and exact analytical and numerical solutions are even more difficult to obtain.

2.2 Loss circulation

Loss circulation is the migration of drilling fluids through the pores, fissures and high permeability zones in rock formations. The loss of drilling fluids and its accompanying problems represent a major fraction of the total drilling cost in most fields. Calcada et al.[26] reported that drilling fluids of varying compositions represent 15-18% of the total drilling cost. In turn, 10-20% of the total cost of production and exploration wells can be attributed to fluid loss circulation. It is estimated that over 2 billion USD is spent annually in combating and mitigating the problem of lost circulation.[27]

Overbalanced drilling (in which the well pressure is higher than the formation pressure) is a common practice in the Brazil oil industry. This practice, coupled with the occurrence of naturally fractured reservoir zones further induces drilling mud loss. It becomes more complicated when the fracture networks are complex and difficult to plug. According to Waldmann et al.[28], 1 out of 3 wells drilled by PETROBRAS have lost circulation problems. This generates additional net costs and in extreme cases compromises completion integrity, operational safety and the environment, thus increasing non-productive time. Palsson et al.[29] described a series of lost circulation events in the drilling of a geothermal well in the Krafla field in Iceland (designed to reach a depth of 4500 m). Over 60 L/s of mud losses occurred at a depth of 2043 m; this could not be stopped by the drilling team and the remedy was to replace the mud with water. Breakage of the bottomhole assembly occurred at 2101 m; due to unsuccessful fishing, the well was eventually sidetracked and terminated. In the Azar field of Iran, complete loss of the drilling fluid was occasionally observed.[30] A decrease in the mud weight was the adopted mitigation strategy for this problem and this resulted in a mud gain of 1.59 L/s. These practical challenges highlighted are indications of the severity of this problem to the oil and gas industry.

2.3 Wellbore stability challenges

During drilling, several process disturbances that could cause pressure fluctuations might occur, and drilling operators must ensure that a safe operating pressure window is maintained for the avoidance of formation fracturing (extreme OBD) and unwanted fluid influx/kicks (UBD) which may lead to blowouts. The small tolerance between pore pressure and fracture pressure gradients is of paramount concern to drilling engineers.[31–33] Fig. 2 shows a blowout preventer (BOP) which is usually installed at the top of the annulus to avoid the outflow of formation fluids. When uncontrolled flow of hydrocarbons occurs, a hard shut-in may be performed by closing the BOP and the well choke. Some instrumentation used for measuring the choke pressure, pump pressure and annular flowrate to monitor wellbore stability are also shown in Fig. 2. As drilling progresses (Fig. 2), the well length increases and the wellbore is exposed to more of the formation's high pressure. This gradual-to-rapid exposure (depending on the penetration rate) constitutes a disturbance to the overall system's stability that must be controlled. Since the drillstring is made up of many pipe segments which must be connected together (to reach the reservoir kilometres away), the pipe connection procedure can result in wellbore instabilities.[34,35] This is because the drill bit rotation and the mud pump must be stopped and restarted for the new pipes to be mounted or installed.

Figure 2: A managed pressure drilling system showing unwanted gas influx from the reservoir.[11]

This stop-start procedure significantly influences the fluid flowrates and in turn the bottomhole pressure. Another complication is that downhole measurements are usually unavailable, and mostly topside measurements (such as the inlet pressure at the well choke and standpipe) can be utilized for control purposes.[35,36] The immense industrial significance of wellbore stability and control can be derived from the Macondo oil well blowout incident across the Gulf of Mexico in 2010, which lasted for 87 days.[37] Since this catastrophe, the level of automation in the oil and gas industry has continued to evolve due to severe economic implications and stringent health and safety standards/constraints. This has paved way for the advancements and implementation of control methods in the oil and gas industry, given the highly complex extended-reach and multilaterals wells the industry must drill to access oil and gas in harsh environmental and climatic conditions.

Event detection (e.g. kicks) and post-drilling data analysis require the application of sophisticated downhole sensors. Challenges such as repeated rigorous calibration, sensor drift, poor quality data at extreme downhole conditions, high cost and false alarms that exist in real field operations provide opportunities for performance improvements of these devices. Pournazari et al.[38] provided developed a pattern recognition algorithm that allows for real time calibration and speedy analysis of sensor patterns for event identification such as kicks. Chhantyal et al.[39] also emphasized the need for reliable and accurate downhole flow measurements using robust sensors. They highlighted that the accuracy of the sensors must be maintained for wide range of drilling fluid viscosity (1-200 cP) and density (1000-

2160 kg/m^3). The combination of machine learning algorithms and physics-based modelling holds a promising potential for improved sensor accuracy.

2.4 Stuck drillpipe and slow drilling rates

Well drilling in the oil and gas industry is usually done with a highly flexible rotating drill string (to which the drill bit is attached), and this produces a trajectory that is never perfectly vertical. This implies that the drillpipe makes contact with the walls of the wellbore at numerous positions several meters downhole.[17] Thus, frictional resistance generated may require extra torque than otherwise required to turn the drillpipe and the bit; this translates to an unacceptable power consumption. Similarly, the drill string's tripping (lowering into and pulling out of the wellbore) movements often causes a differential sticking effect on the mud cake (residue generated from drilling mud due to pressure difference between the formation and the wellbore) deposited around the borehole wall. This causes the drill string to be trapped and the pulling power of the rig is unable to release the string from the mud cake.[40] Loosely compacted and fractured formations and gravels may also collapse into the wellbore as drilling progresses, thus forming a bridge around the drillstring or jamming the drill string. The clay swelling effect of certain reactive formations in contact with water-base muds may also constrict the wellbore. Poor hole cleaning which causes cuttings accumulation may also cause stuck pipe problems.[41,42]

Due to the complex geological properties of most reservoirs, it is expected that the layers of rock formations will vary in their hardness. This translates to different penetration rates of the drill bit through these layers. The mechanical performance of the drilling machinery as typically indicated by the quality of drill bit and extent of pipe rotation attainable will largely affect the overall efficiency of the operation. Furthermore, since drilling muds, cool, lubricate, and transmit hydraulic energy, the rheological properties of these fluids will largely affect the penetration rate.

In 1993, the Dutch petroleum company (Nederlandse Aardolie Maatschappij – NAM) reported a number of major cost overruns due to stuck drillpipe problems.[43,44] According to the report, the cost incurred to handle stuck equipment incidents amounted to US$15 million (5% of entire drilling capital expenditure). These problems are likely to increase despite technological advancements over the last decade. This is because the ever-growing complexity of exploration activities (large diameter wellbores with high inclination angle, extended reach and multilateral structures) in challenging offshore environments with very harsh conditions such as the Arctic.

2.5 Complex wellbore geometries.

Drilling wells with deviated/horizontal geometries and multiple branches to improve recovery from multiple reservoir zones by commingling production have become common in the oil and gas industry. A successfully designed and implemented multilateral well that replaces several vertical wells may drastically reduce the overall completion costs; thus enhancing field profitability. However, the accompanying complexities of these well types increase the risks of failure.[45] Compared to vertical wells, sophisticated mechanical steering tools are required to ensure the planned trajectory is attained. Hence, correctly positioning and maintaining the horizontal well section within the target reservoir (layer) thickness is of utmost concern to drilling engineers.[46,47] Furthermore, ensuring proper zonal isolation in each of the well sections is also a major challenge with horizontal and multilateral wells. If the drilling crew fails to maintain zonal isolation, downhole annular pressure control becomes extremely difficult and blowouts may occur. Depending on the well perforation intervals adopted, these wells may be subsequently exposed to production related problems such as water and gas coning and sand production. Hence, challenges of deviated well drilling are largely influenced by the expected fluid delivery rates of the well.

3.0 Previous Contributions: A Process Systems Engineering (PSE) Perspective

Although there has been an enormous body of work on high-fidelity multiscale modeling and optimization by the PSE community on production-oriented upstream operations, (a few review papers adequately covering those), there is an equally important (albeit perhaps smaller, in comparison) body of work addressing drilling-oriented operations. Moreover, a critical literature mass has appeared in SPE sources and audiences, somewhat further afield from the standard PSE venues. In this section, a PSE perspective to addressing some of the earlier identified problems is presented. The discussion herein is categorised into four subsections on control and automation of managed pressure drilling, real time monitoring (using high fidelity and lower order models), drilling optimisation and artificial intelligence techniques for solving drilling-related problems.

3.1 Drilling optimisation

Depending on the intended application within the multifaceted nature of a drilling program, mathematical optimisation techniques have shown great potential for operation improvement. Downhole pressure control using NMPC schemes is one of the most explored aspects as far as optimisation is concerned.[33,48,49] However, the rate of penetration is a parameter drilling engineers aim to always maximise. Eren and Ozbayoglu[50] applied multiple linear regression for parameter estimation of an ROP equation (in terms of the WOB, formation depth and rotary speed) based on real time data. The authors sought to arrive at an optimisation methodology that utilises past drilling data while predicting the drilling trend for optimum drilling parameter selection and cost savings; this was achieved. Based on a similar concept, Rommetveit et al.[51] similarly, introduced a bit load optimisation module that modulates rotary speed and WOB for an optimal ROP. With the application of their solution algorithms in the module, they reported that ROP increased by 15-30%. The application of ROP optimisation software developed by Chapman et al.[52] and Detournay et al.[53] has shown the possibility of attaining reduced equipment vibration and equipment failure. The software employs a formulation that relates the ROP (depth of cut per revolution) to the WOB and bit torque.

The concept of mechanical specific energy (MSE), introduced by Dupriest & Koederitz[54] evaluates the efficiency of drill bits in real time; this approach has been readily applied by drilling operators as an optimisation tool in combination with drilling logs for decision support[55]. Koederitz and Johnson[56], achieved semi-autonomous steering optimisation during drilling using the MSE concept. A simulated annealing optimisation algorithm coupled with an abductive neural network was applied by Lee et al.[57] for the prediction of drilling performance (torque, tool life, metal removal rate, and thrust force) with drill diameter, cuttings speed and feed rate as the input parameters. Several drilling experimental tests performed confirmed the effectiveness of this approach. Enhanced visualisation and interpretation techniques in state-of-the-art drilling simulators provide an optimised 3D tracking of the well trajectory as drilling progresses.[58] It was highlighted that, drilling optimisation here is not static because drilling parameters vary as the depth increases. Rather it is a dynamic function of depth. Hence constantly varying constraints (e.g. due to formation heterogeneities and strengths) and varying optimised parameters cannot be avoided if drilling cost must be minimised. Several other simulation packages for optimising drill string torque and drag, wellbore propagation, well trajectory (inclination and azimuth) and downhole steering have been developed as detailed in Siguira et al.[58]. It is evident from these contributions that classical optimisation in the industry is usually a semi-heuristic based approach that relies on several simulation studies; the use of standard mathematical optimisation concepts has rarely been adopted in the industry.

Drilling rigs are not only used in drilling new wells, but also in servicing existing ones (workover). However, the number of new target well sites and existing wells usually exceeds the number of available drilling rigs; thus increasing the complexity of the operation.[59] This necessitates the determination of optimal rig-to-well allocation, rig routing and scheduling (collectively described as *workover rig scheduling* – WRS). Although geared towards production optimisation, this aspect of drilling has received considerable attention from Tavallali et al.[60] and Gupta and Grossmann[61]. Rigorous mixed integer nonlinear/linear optimisation formulations (with thousands of binary variables) have been formulated with adaptive algorithms for efficient solutions, thus aiding field development decisions. Such depth of work has hardly been adapted to other drilling aspects.

Despite being a subject of intensive research, the transport of cuttings has received little or no contribution from optimisation experts. This may be due to the prevalence of rigorous fluid/particle dynamics simulations used in studying the transport phenomena of cuttings; such simulations are not readily adaptable to an optimisation routine due to computational cost required at each iteration; furthermore, coupling the CFD solver with an optimisation solver is also not an easy task.[62,63] However, several robust empirical cuttings transport models developed by Ozbayoglu and co-workers[64–66] provide room for nonlinear optimisation studies in this regard. There is also a potential for embedding ANN proxy models based on numerous reasonably timed and validated CFD simulations within a stochastic optimisation framework such as genetic algorithm (GA). It is also worth mentioning that the uncertainty associated with measured drilling parameters is often very high. For example, highly uncertain hole calliper measurements could result in erroneous estimations of the hydraulic diameter and in turn fluid superficial velocities and frictional pressure loss; uncertainty of the MD-TVD relationship would inevitably affect the calculated hydrostatic effect. Fluid properties must also be corrected for pressure and temperature deviations using PVT models.[67] Hence, the industrial applicability of drilling models and optimisation algorithms is dependent on their capabilities to address this inevitable uncertainty in the governing parameters.

3.2 Real-time monitoring using high fidelity and reduced order models

Nygaard and Naevdal[68] highlighted that pressure control during pipe connections is often challenged by temporal unavailability of downhole data from a mud pulse telemetry system or via a wired drill pipe. This is because the signal transmission is dependent on the mud circulation, which is stopped during pipe connections. Furthermore, signal cables must be disconnected during connection procedures. Recently, it has been shown that electromagnetic transmission systems may be utilised for data transmission from the rock formation to the surface; however, the attenuation of electromagnetic signals and reduced data quality in very deep wells (> 2500 m) is an encumbrance[68,69]. These challenges imply that pressure control systems must rely on sufficiently accurate dynamic well hydraulic models. The scarcity of downhole data is another (if not the main) motivation for the use of robust and calibrated models in most MPD operations.[11,48] Models may be used for simulation purposes (during which control parameters may be tuned, tested, and verified); furthermore, models may be used for estimating the states of the process, especially when noisy measurements occur. Future process behaviour may also be predicted by the model and future set points selected.[70–74]

Model-based control techniques applied in oil and gas drilling systems often impose limitations on the structure of reduced order models that may be applied for system control. Aarsnes et al.[75] classified reduced order models based on complexity and physical interpretations of the simplifications adopted. Their classification categorizes these models into Reduced Drift Flux Models, Lumped Order Lower Models, 1-phase models and Lagrangian models. The performances of these reduced order models when compared to an industrially implemented high fidelity simulator are shown in Fig. 3. In evaluating the models performance, three practical scenarios are adopted (MPD gas kick, pipe connections during UBD, different drawdowns from a UBD gas well - UBD envelope). Compared to the other models, the lower order lumped model showed the poorest performance. A lower-order drill string dynamics model developed by Ke and Song[76] has been utilised for control purposes. The model incorporates axial motion and torsional vibration of the drill string and the bit-rock interactions. This model shows good performance when validated with a high-fidelity drilling dynamics model. The application of local model order reduction techniques for nonlinear PDE systems such as, Proper Orthogonal Decomposition (POD), Dynamic Model Decomposition (DMD) and Ensemble Kalman Filters (EnKF) have been applied to several other oil and gas systems, but have received little attention in drilling systems. These methods often rely on analysing information obtained from a series of observational data of high-dimensional systems to identify coherent patterns embedded in such systems.[77–79] The computational cost required for the development of these reduced order models and their need for frequent calibration, may constitute reasons for their limited application in drilling systems. Notwithstanding, a quantitative exploration of these reduced model types is required for drilling systems to verify their potential in comparison to the reduced order models detailed in Aarsnes et al.[75]

Figure 3: Bottomhole pressure and wellhead pressure trends for three operational scenarios and the evaluation of lower order models (mechanistic and reduced Drift Flux Models, 1-phase model, Hauge et al.[36] model and the low order lumped model) in comparison with a high fidelity multiphase flow simulator OLGA.[75]

During mud circulation, a very complex multiphase flow scenario exists; the liquid mud phase interacts with possible fluid influx (gas, oil & water) in the presence of solid rock cuttings that evolve. This occurrence creates an avenue for the application of fluid dynamics concepts in process control (Fig. 3). In addition to multiphase flow and wellbore hydraulics, rigorous descriptions of drill string dynamics[58], rate of penetration and dynamic response of topside equipment are also essential for a full description of the entire process (first principles models). Apart from being difficult and time consuming to develop, the combination of these rigorous models is computationally demanding when embedded in a control scheme (due to extreme nonlinearity). However, since the emphasis here is placed on pressure control, simplifying assumptions (such as a uniform fluid distribution in the well) are usually made to reduce the complexity from a PDE based model (used in classical fluid dynamics) to a system of ordinary differential equations (lower order models which focus on fluid flow and the impact on wellbore pressure). However, Nygaard and Naedval[68] have reported that un-modelled effects due to severe approximations may cause errors in the prediction of the downhole pressures; thus resulting in severe costly deviations from the downhole pressure. Although detailed first principles multiphase flow models have been used for simulation and control purposes in[14,80], the scarcity of some model parameters (which are not easily measured in real drilling operations) places a demand on empiricism for model adjustment purposes. Despite the applicability of first principles models (over a wide range of operating conditions – less tuning requirements compared to empirical models), closed loop empirical model identification can be costly and disruptive to MPD operations; thus causing instabilities.

Controller stability is a function of model accuracy; this is because fewer iterations are required to match the model to the process output compared to inaccurate models. With the occurrence of sensor failure and loss of feedback signals (common in MPD operations), maintaining control via high fidelity simulators working in parallel with lower order empirical models becomes very important. Hence, operating and controlling drilling programs with both classes of models has delivered huge benefits while achieving acceptable sustainability, as demonstrated by Eaton and co-workers.[14] The need for speedy computations and increased accuracy has inspired the development of several low order control models in the drilling industry. Some of the prevalently used models include the SINTEF's model[81] and Stammes et al.[73] hydraulic model. A subset of these empirical models that describe specific drilling properties such as rate of penetration, frictional pressure drop, rotational dynamics and weight on bit are also under continuous development.[82] Asides the literature developed models, several proprietary simulation models (embedded in commercial simulators) have been developed by different oil companies. However, the numerous developments of advanced modelling tools produced by the academia in the last decade have not fully gained industrial acceptance and implementation. A perspective of industrial operators on the use these models as reported by Sugiura et al.[58] revealed that model validation and benchmarking must be carried out; with limitations and assumptions explicitly stated if industrial applicability is desired. The capability of these models to quantify an envelope of safe operating conditions (based on continuous calculation of the system's boundaries) using the current state of the well and topside machine limitations is also an important attribute of these models affecting their industrial acceptability.[35]

Real-time measurement techniques used in the drilling industry include wired coiled tubing telemetry (WCTT), Mud Pulse Telemetry (MPT), Wired Drillpipe Telemetry (WDPT), Acoustic Telemetry (AT), and Wireless Electromagnetic Telemetry (WET). The performances of these technologies are summarised in Table 1. By using data (manipulated, controlled and inputs) from these telemetric systems, a calibrated annular flow model may be written and controllers designed to achieve a stable annular pressure as described by an objective function.[82]

Table 1: A comparative performance of LWD telemetry technologies.[83]

3.3 Control and automation of managed pressure drilling

Although drilling operations possess some elements of a mechanical system with important associating concerns (vibration control, equipment performance monitoring and maintenance), process control is similarly important. In the latter, issues like mud flow, surface and downhole pressure management become important for operational efficiency and safety.[84] Managed pressure drilling (MPD) is an emerging technology formed out of this necessity of precise wellbore pressure control within tight bounds. The use of a closed annulus, valves and additional pumps in addition to the standard main pump makes MPD different in contrast to a conventional drilling process.[48,85] In conventional drilling, drill mud is returned to the surface through an open line at atmospheric pressure. The closed circulation nature of MPD operations provides better flexibility than conventional drilling in which pressure control is usually achieved by pump rate and mud weight adjustments alone. According the SPE/IADC, *MPD is an adaptive drilling process used precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic profile accordingly*. The intricate nature of such a system requires the application of multivariate control strategies, for which model predictive control (MPC) is often preferred; IMC and PI control schemes have also been frequently adopted.[49,82,86] Furthermore, the multiplicity of operational scenarios and the simultaneous considerations needed for the highly interdependent variables (weight on bit, penetration rate, surface flowrates, pressures etc.) characterising the MPD system imply that manual procedures and workflows cannot guarantee the continuous satisfaction of strict pressure constraints. Control schemes like MPC provide coordinated operability of the process via the automation of lower-level decisions, thus allowing humans to attend to higher-level decisions.[69,87,88]

In exploring the shallow gas Nagar prospect in the southern coast of Myanmar, PETRONAS had to apply MPD technology for quick kick detection and accurate pressure control to maintain economic viability of the project[89]. It was estimated that within 3 minutes, the installed system would have to detect and shut in a gas influx and circulate the gas out the wellbore, while controlling the BHP within safe limits of ± 15 psi during active drilling and ± 45 psi during drillpipe connection procedures. This is a classic example that demonstrates the complicated nature of the well control problem. Tackling this challenge with the help of three other service providers made PETRONAS the first to develop and implement an automated real-time pressure control system while drilling. Further details on the implementation of their dynamic annular pressure control (DAPC) system and the lessons learned during the application of this technology can be found in Fredericks et al.[89] The probability of such successful implementation can be increased if high quality downhole data becomes available through wired drill pipes (or competitive technology).

Figure 4: Diagram of a switched control system.[14]

High-speed telemetry systems have been applied in the studies of Park et al.[71], Pixton et al.[69] and Asgharzadeh Shishvan et al.[90] for the regulation and control of ROP, BHP and WOB during MPD operations. A nonlinear multivariate MPC framework that directly utilizes downhole and surface data is utilised in these studies. Asgharzadeh Shishvan et al.[82] also applied a similar control strategy with further adjustments of other conditions such as the drill pipe rotation, bottomhole pressure and hook position for dual gradient drilling operations. Their proposed algorithm showed good performance in a high-fidelity simulation environment. When downhole data is unavailable, a real-time hydraulics model is a reliable option that can predict downhole conditions based on surface data of pumps rates and chokes settings. With the obvious inability to use high-fidelity models for real time control purposes (due to computational cost), Eaton et al.[14] developed a switched control scheme (Fig. 4) that implements a linear empirical control model of satisfactory accuracy in comparison to high fidelity models. A lower order NMPC controller is also utilised for maintaining control over the process during empirical model identification tasks (using simulated data from a high fidelity model); thus reducing the computational cost. This strategy allows for the inclusion of the slow but very accurate high-fidelity model without interrupting the process. The frequent of gas kicks in most drilling operations has warranted the development of a novel model-based control scheme for kick detection and attenuation by means of real-time pore pressure estimation;[31,36] the proposed method also lends itself to loss mitigation purposes in naturally fractured formations. Robust controller design using linear matrix inequalities has been formulated for kick handling purposes by Aarsnes et al.[33]. Handling gas influx during MPD operations depends on the size of the kick (Fig. 5); while small kicks may be circulated out by increasing surface back pressure, larger kicks may be handled using standard well control procedures (such as shutting in the well). This is because a planned limit for the influx indicator is usually defined before the MPD operation.[48] If this limit is exceeded, the conventional well control is usually implemented with considerations on the operational limits of the choke valve and pressure margins that could fracture the formation.[35] It is obvious that these considerations are not only dependent on the prevailing conditions of the downhole conditions but also on the field and the equipment capabilities.

Although downhole uncertainty continues to drive automation-related research endeavours (with increasing contributions in the last decade), the industrial implementation of these automated control methods has remained at a low level.[35,58] A further complication that limits the holistic automation of drilling systems is that several independent software solutions exist that address the different aspects of the drilling operation in isolation.[9,91] Integrating all solutions within a single control framework is not a trivial task. In order to address this challenge, a control hierarchy design for production optimisation by Saputelli et al.[92] was adapted to drilling automation operations. The multilevel control approach comprises a feedback control level, a supervisory control level and an optimisation level. Despite these advancements, Breyholtz and Nikolaou[35] highlighted that it is impossible for the automation design to foresee all possibilities in such a complex and uncertain operation as drilling, hence the driller must be able to manually take over the operation at highly critical moments. Furthermore, more recent advancements in sensor design[38,39] also emphasize the need for occasional manual intervention due sensor drift (from calibration).

Figure 5: Bottomhole pressure control during a kick at 80 mins.[93]

The application a dynamic programming (DP) approach for the downhole control and optimisation of a drilling system was presented by Ke and Song.[76] They constructed a novel drilling dynamics model and a customised DP algorithm for improved computation efficiency and controller robustness as validated by a higher order dynamic model. Tian and Song[12] designed a two-chain observer strategy to estimate real time states of the drilling system dynamics and the prevalent downhole conditions. Their design showed good performance in addressing measurement/signal delays of mud pulse telemetry systems.

Advanced methodologies such as Dynamic Mode Decomposition with control (DMDc) have recently been applied in hydraulic fracturing processes for accurate representation of high-dimensional complex data associated with this process.[79] Control schemes that determine an optimal pumping schedule and regulate the uniformity of proppant bank heights along fractures have also been developed by Kwon and co-workers.[77–79,94,95] A framework for closed-loop model-based control of hydraulic fracturing processes (fracture propagation, proppant bank growth and fluid-solid transport phenomena) was developed by Gu and Hoo.[96,97] Good attenuation of disturbances to the system were obtained using a

Quadratic-Dynamic Matric Controller (QDMC). Autonomous directional drilling using a mud motor and rotary steerable systems is also an area that has received attention from the process systems and control community using MPC technology.[98,99] These systems are often formulated and solved as Mixed Integer Quadratic Programs due to the presence of binary and continuous quantities. Satisfactory trajectory control of the drillstring while satisfying operational constraints has been achieved as detailed in Zhao et al.[99]

It is thus evident that the applications of the process control techniques discussed herein show good potential for increased drilling efficiency, safety and reduced cost if they are well integrated into drilling processes.

3.4 Application of artificial intelligence techniques

With increasing industrial demand for intelligent drilling automation and optimisation, artificial intelligence holds a promising potential for bridging the gap between the two tasks, improving current drilling practices and real time decision making. The most widely used techniques include artificial neural networks, fuzzy logic, genetic algorithms, support vector machines and hybrid techniques.[100] Such computational intelligent methods can be used to analyse data from sensors, survey data, geology data and the well plan in order to make real-time closed-loop predictions for fast reaction (prompt flags of potential anomalies) and resolution of drilling dysfunctions.[101] Big data analytics is also an emerging trend in the oil and gas industry that aids the application of AI techniques.[102] After generating a dataset of specific offshore drilling information using fuzzy logic, Mendes et al.[103] implemented a genetic algorithm for the prediction of feasible trajectories for wells and directional drilling parameters using retrieved datasets of similar drilling scenarios. Popa et al.[104] applied case-based reasoning (an AI technique) for the selection of the optimum hole cleaning procedure in unconsolidated sands by collating datasets from nearly 5000 wells; an accuracy of 80% between AI proposed methods and those actually implemented was observed. Wang et al.[105] applied an artificial neural network model developed by British Petroleum (BP) for the optimal selection of deep-water floating platforms (a decision dependent on many interconnected variables). In solving this model, the Levenberg-Marquardt algorithm was applied. This resulted in 70% accuracy for 10 datasets with limited errors, thus validating this quantitative approach (which would have been otherwise carried using engineering judgement alone).

The capability of ANN for accurate real time prediction of frictional drag and drill string contact force as a function of the radial clearance, slack-off load, bending stiffness and other drilling parameters was demonstrated by Sadiq and Gharbi.[106] This prediction has tremendous importance when time consumption due to expensive downhole trips (for BHA replacement) are to be avoided. Rooki et al.[107] applied an experimentally validated back propagation neural network coupled with multiple linear regression for the prediction of cuttings concentration in an annular wellbore during foam drilling. They compared the performance of their ANN model with the results of a mechanistic cuttings transport model and realised an absolute average deviation of less than 6%. A similar approach by Al-Azani et al.[108] was adopted for hole cleaning; this was however based on 116 experimental data records. Chamkalani et al.[109] developed a pattern recognition neural network (Fig. 6) for the drilling optimisation in shaly formations. An extensive discussion on the application of AI for well integrity problems, operational troubleshooting, real time drilling optimisation and well planning can be found in Bello et al.[100] In addition, the application of AI techniques in drilling fluid engineering has been comprehensively reviewed by Agwu et al.[110,111] The highlighted applications include rheological parameter determination of various drilling fluids,[112,113] prediction of loss circulation,[114] differential pipe sticking,[115] fluid flow patterns,[116] downhole fluid properties,[117] mud velocity/flowrates and pressure drop.[118]

Figure 6: Schematic structure of a pattern recognition network.[109]

It should be pointed out that AI techniques should be applied with care; the necessity of maintaining sensible physical interpretations of predictions cannot be overemphasised, despite high values of statistical correlation indicators (RSME, R^2), which may be misleading. A comparative analysis[111] based on different AI techniques applied in the drilling industry showed that although ANN, SVM, fuzzy logic and GA are robust against noise (in data); whereas, fuzzy logic ranks highest in terms of convergence speed. Susceptibility to overfitting, limitations of data volume, generalisation and self-organising ability are other criteria that may be assessed when choosing these AI methods.

4.0 Previous Contributions: A fluid & particle dynamics perspective

Contributions from the field of fluid dynamics have been mainly targeted towards cuttings removal and the rheological performance of drilling muds at unfavourable downhole conditions. The development of good rheological designs and an accurate understanding of mud shearing behaviour has been aided by advancements in multiphase flow description using physics-based phenomenological models.[62,119] Due to the profound economic implications of poor/late rheological planning, drilling engineers are constantly faced with several intricate questions; some of which include: what flow properties are associated/expected with a given drilling mud? Can the level of downhole blockage (due to accumulated cuttings) be inferred from flow rate and pressure drop data? In the worst scenario of sever cuttings accumulation, what is the optimal/critical flow rate to lift cuttings back into full suspension.[120,121] Furthermore, the occurrence of dense fluid-particle flows (granular flows) in which inter-particle collisions are a dominant feature in drilling operations;[122] these flows can be very different to single-phase flows of drilling muds. Accurate understanding of different forms of granular flow have been made possible by the use of robust particle collision models (hard and soft particle models) embedded in state of the art computer simulators;[123] thus making it possible to describe slow and rapid granular flows effectively.

4.1 Drilling fluids and rheological models

Although many requirements (cooling and cleaning the bit, maintaining wellbore stability, reduce pipe friction) are placed on drilling fluids, their originally intended purpose was for the removal of rock cuttings (Fig. 8) generated by the weight and rotary motion of the drill bit.[17] Field decisions regarding the choice of drilling fluid for a particular project are usually driven by cost, technical performance and environmental impact. Drilling fluids may be categorised into freshwater systems, saltwater systems, oil- or synthetic-based systems and pneumatic (air, foam, mist, gas) systems as shown in Fig. 7. Water-base muds (WBMs) are prevalent in the industry compared to oil-base muds (OBMs) which are more expensive, but provide excellent lubricity.[124] Pneumatic muds are the best candidate when there is high risk of formation damage and lost circulation.

The performance of these fluids is mostly understood through their shearing behaviour, determined from experiments (using spindle mixers/blenders, viscometers, filter and stability testers) and rheological modelling efforts (using power law-PL, Herschel Bulkley-HB, Bingham plastic-BP models).[113,125,126] The applicability of these rheological models is dependent on the mud components/additives (surfactants, emulsifiers, lubricants corrosion inhibitors etc.). Furthermore, mud performance is not only dependent on the fluid rheology, but also on the flow regime (laminar, transitional or turbulent) in the drillpipe and the annulus as determined by the Reynolds number.[127] With the advent of computational fluid dynamics, and advances in high performance computing, several studies have emerged that address Newtonian and non-Newtonian fluid behaviour in channels of different geometries.[128,129] Typical field flow conditions and flow phenomena, which can be difficult to measure or replicate at laboratory conditions can be readily modelled and their impacts on the fluid performance understood using CFD.

Figure 7: Classification of drilling fluids according to their principal constituent.[17]

Hussain and Sharif[130] demonstrated via CFD calculations the existence of a secondary flow zone in conjunction with a primary axial helical flow in the wider section of an eccentric annulus using a viscoplastic HB fluid. They also evaluated the impact of a blockage height (e.g. caused by accumulated cuttings) and inner pipe rotation on this secondary flow region. In furtherance to this observation, it was discovered via numerical simulations (using a yield-PL fluid) that velocity profiles in eccentric annuli are too complicated to be represented by an average velocity.[131] Rooki et al.[112] showed that the PL model better described the rheological properties of foam compared to the HB model. Zaisha et al.[132] pointed out the limitations of the continuous viscoplastic approximation method in bypassing the shear stress discontinuity when solving the governing equations of a yield viscoplastic fluid flowing through concentric and eccentric annuli. A numerical procedure that adequately resolves this problem for HB fluids was proposed in their work. A combination of experimental and CFD-based simulations has been adopted for the study of steady state and transient mud (liquid) shearing behaviour at varying degrees of eccentricity and drillpipe rotation.[125,133–135] Duan et al.[136] also examined the impact of pipe rotation on foam velocity profiles and pressure losses during drilling using experiments and CFD. It was discovered that the maximum axial velocity core of an eccentric wellbore is shifted in the direction of drill pipe motion. However, when a cuttings bed occurs, the core shifts to the opposite direction of drill pipe motion. More contributions on the performance of foam-based fluids in drilling (particularly related to cuttings transport) can be found in review paper of Yan et al.[137]

4.2 Recent developments for improved mud performance

Advancements in drilling mud technology have mostly centred on the design of new additives for performance enhancement under harsh downhole conditions (high temperature and pressure) where performance deterioration is likely to occur.[138–140] In this section, the application of nanoparticles – NP (such as Fe_2O_3, Fe_3O_4, SiO_2 etc.)[141] and supercritical fluids are the main advancements discussed. Smart (nanoparticle-based) drilling fluids enable better controllability of in-situ fluid rheology, thus facilitating drilling programs in a variety of reservoir environments.[142] It is expected that these particles further complicate the fluid's rheological behaviour; however, first principles rheological modelling (HB model) carried out by Gerogiorgis et al.[143,144] provided clarifications to this complexity. Several experimental studies that demonstrate the potential of nanoparticle-based drilling fluids for wellbore strengthening, cuttings lifting capacity, thermal and magnetic performance enhancement for viscosity control are documented in the review by Vryzas and Kelessidis.[145]

Research in the area of supercritical fluids (which exhibit physical-chemical properties between those of liquids and gases) has increased over the years. Supercritical carbon dioxide (SCCO2) possesses remarkable viscosity characteristics at downhole conditions; it has been successfully applied for the removal of cuttings,[146–148] reduction of mechanical drilling forces and efficient cooling of the drill head. A study by Kolle,[149] suggested that SCCO2 is useful in providing better jet erosion (jet-assisted drilling for cutting through rock formations) and penetration rates compared to water-based fluids. Gupta et al.[150] developed a model to simulate potential scenarios during drilling operations with a SCCO2. From model simulations performed, it was discovered that the large pressure drop across the nozzles allows rapid change of SCCO2 from liquid to gas; thus accelerating cuttings movement while maintaining UBD conditions. They further demonstrated the economic and environmental viability of the operation in terms of CO2 sequestration and CO2-based enhanced oil recovery.

4.3 Wellbore cleaning/cuttings transport and summary of published findings

Numerous interdependent factors and the inherent complexity of the transport process pose challenges to efficient wellbore cleaning (Fig. 8). These factors can be generally classified into the operational parameters (drill bit penetration rate, drillpipe rotation, circulation velocity etc.), rock and fluid parameters (particle shape, size and density; fluid density, composition and rheological behaviour) and geometrical parameters of the wellbore (diameter, length, inclination, eccentricity). The importance of understanding the effects of these independent parameters on the efficiency of the wellbore cleaning process has been long recognised.[41,151–154] Previous research contributions have mostly accounted for the influence of these parameters in groups, because, considering all parameters in a single study would be very cumbersome from both experimental and modelling perspectives.[155–157]

Although the general term 'cuttings transport efficiency' has been used thus far, it worth mentioning a set of dependent parameters exist that reflect the efficiency of the cuttings transport process. They include the annular pressure drop, cuttings concentration or volume fraction, cuttings velocity (axial, tangential and radial) and the downhole retainment of drilling mud quality (Fig. 9). As earlier indicated, accurately monitoring and measuring all these parameters (for attaining robust insights into the cuttings transport phenomena), would require sophisticated 3D dynamic visualisation techniques.[158,159] Thus, the limitations of laboratory equipment have thus far guided the parameter sets considered by most research groups.

Figure 8: Particle transport in the presence of a mainstream non-Newtonian fluid during drilling operations.[160]

From a modelling perspective, several 1D mechanistic and 2D layer models have been previously constructed.[161–165] These models have shown good potential for predicting experimental measurements with additional insights provided by sensitivity analyses. More recently, the application of 3D Computation Fluid Dynamics (CFD) tools for studying cuttings transport phenomena has gained prevalence due to its unparalleled ability to predict experimental measurements. Furthermore, the accompanying spatio-temporal visualisations obtainable via this approach make it possible for direct qualitative comparisons with experimental observations. The increasing number of CFD-based contributions can also be attributed to the advancements in computational power coupled with robust algorithms for solving the underlying equations.[166,167] In the following sections of this article, we extensively explore the findings of several experimental and simulation-based contributions to the field while elucidating some fundamental aspects of both approaches. We also analyse the challenges faced from both perspectives and proffer new research directions that could improve the state of the art as far the scientific understanding of cuttings transport operations is concerned.

Figure 9: Factors affecting drill cuttings transport efficiency.

4.3.1 Experimental studies

In order to complement multiphase flow modelling efforts and assess/verify their industrial applicability, experimental measurements under a controlled set of conditions are inevitable. The construction of a flow loop that replicates the actual wellbore conditions (high temperatures and pressures, wellbore lengths reaching several kilometres with large diameters etc.) in the industry is not realisable; hence, downscaling typical parameters obtainable on a field scale is vital for carrying out multiphase flow studies under laboratory conditions (Fig. 10). Although several flow loops[168,169] for studying multiphase flows in pipes exist around the world, there are few that mimic the annular geometry encountered in drilling operations. Despite this scarcity, the number of experimental investigations of cuttings transport has continued to increase over the past decade.[66,118,159,170–179] A summary of our observations from various published studies is presented next.

Figure 10: Typical components of an experimental set-up for cuttings transport (a);[180] Experimental testing facility at the University of Tulsa (b).[181]

- A cuttings injection tank, mud tank, annular test section, compressor, pump, flow/pressure measuring (robust instrumentation) and visualisation equipment are the main components of most experimental testing facilities.
- Majority of the studies shown analysed involve a wellbore of perfectly spherical cross-section. However, Taghipour et al.[182] performed transport experiments over a tortuous non-circular wellbore that imitates real field operations.
- The annular cuttings concentration (via the cuttings bed height) is the most widely used metric for assessing the efficiency of cuttings transport. The development of sophisticated camera systems aid this observation.
- The impact of particle shape on the efficiency of cuttings transport has not been widely studied by means of experiments; spherical Sand particles with density of approximately 2650 kg/m^3 are dominantly applied.
- For foam-based experiments, foam density is a parameter that is hardly reported, thus making it difficult to use such experimental studies for model validation purposes.
- The inlet volume fraction of cuttings into the annulus is also scarcely reported; the specification of boundary conditions in most CFD simulation requires this parameter; however, Han et al.[183] and Osgouei[155] clearly state this parameter in their experiments, thus making them suitable options for validation studies.
- Polymer-based water drilling muds are the most applied. Few studies[170,179,184] have applied oil base muds for in their work with superior performance of the OBM observed compared to WBM.
- The University of Tulsa drilling research projects (TUDRP) flow loop appears to be largest (30.5 m long, 0.2 m diameter)[158] and one of the most popular experimental facilities used so far in studying cuttings transport.
- There appears to be conflicting findings regarding the ease of transport of smaller particles compared to larger particles, as indicated by the key findings of Sanchez et al.[185] and Li et al.[186]
- Depending on inclination angle, rolling, lifting and settling motions best describe the transport phenomena, with inclination angle, fluid velocity, and fluid rheology being the most influential parameters.

4.3.2 Mechanistic and empirical studies

First principles modelling efforts that describe the transport phenomena and mechanisms of rock cuttings in a wellbore of any configuration are numerous (Fig. 11). Numerous extensions and improvements of earlier developed[160,187,188] mechanistic models have been carried out more recently.[164,165,189]

Figure 11: Schematic representation of a 2-layer (a, b, e) and 3-layer (c, d, f) cuttings transport model with corresponding experimental observations (e, f). The 3-layer assumes the existence of a bottom stationary cuttings layer, a moving middle layer and a top suspension layer; whereas the 2-layer model assumes a bottom stationary layer and a top suspension layer.[138,189,190].

The underlying assumptions of these studies present new opportunities for advancements in the accuracy of these models. However, it is necessary to ascertain (by means of experimental validation) if the inclusion of more physical phenomena results in a significant improvement in model accuracy; this is not usually the case. Furthermore, empirically derived models have become popular with most experimental contributions despite their limited range of application. Mechanistic and empirical modelling research efforts can be categorised based on the model characteristics/limitations and assumptions, flow conditions, system properties, sensitivity analyses performed and the solution method applied. Based on our evaluations of published contributions, we highlight some important trends.

- Mechanistic models are generally either 1D (along the length of the wellbore) or 2D along the cross-sectional area of the wellbore (2-layer and 3-layer models). A detailed sequence of developments on 2-layer and 3-layer mechanistic models can be found in Kelessidis and Bandelis.[138]
- The effect of drillpipe rotation has been hardly considered in most mechanistic models. However, the studies of Naganawa and Noruma[191] (with a simplified rotation model) and Guo et al.[164] are amongst the few that consider this effect.
- The stability enhancing two-step (SETS) method and Crowe's modification of the semi-implicit method for pressure-linked equations (SIMPLE) are the main adopted numerical methods for the system of PDEs, ODEs and AEs in mechanistic models.[162,164,189–191] However, some empirical models (such as that of Larsen et al.[120]) can be solved by hand.
- The assumption of an incompressible solid-fluid system is prevalent despite the usage of compressible foam in some studies. The use of cubic equations of state as demonstrated by Chen et al.[192] is a more reliable method to addressing foam compressible behaviour. Homogenous bubbly flow (where foam is the drilling fluid) is mostly assumed.
- Instant acceleration of influx gas velocity to the mean flow velocity is usually assumed in UBD-based studies.[162,165,180,193]

- Friction pressure loss (between flow layers and between fluid phases and the walls of the wellbore) appears to be the most developed aspect of mechanistic and empirical models.[187,188,191,192,194,195]
- Most cuttings transport modelling studies do not account for loss circulation.
- The use of dimensional analysis (Buckingham-pi theorem) is the widely adopted approach for empirical modelling. Good performance of these models have been verified.[65,66,196–198]
- Majority of these modelling studies show good performance with reasonably low deviations from experimental results, (as indicated in the model validation studies carried out). Experimentally observed phenomena are also observed.[138]

4.3.3 Application of CFD

There are two main approaches for solid-liquid multiphase flow modelling applied in literature; the Euler-Euler approach (consisting of the mixture models, volume of fluid models and the Eulerian models) and the Lagrangian-Eulerian approach (in which particle trajectory calculations are coupled with the Eulerian description of the fluid phase).[123,199] One of the earliest applications of CFD for cuttings transport was by Bilgesu et al.[200] Since then, the application of CFD has continued to increase with accompanying developments in the context of the resolution of particle dynamics (with the use of kinetic theory models, discrete phase models – DPM, discrete element method – DEM), domain discretisation (using finite volume and finite element methods on structured or unstructured grids). Robust turbulence modelling concepts, high performance computing and advanced CFD software (Fig. 12) have also undergone continuous developments. An overview of previous contributions and major highlights with regard to these developments is discussed next.

Figure 12: CFD simulation of cuttings transport in a horizontal annular configuration during drilling.[119]

- The Reynolds Averaged Navier Stokes (RANS) models are the fundamental fluid flow equations implemented in most CFD codes, which are solved to obtain general fluid flow behaviour.
- Compared to Lagrangian-Eulerian (LE) methods, the Eulerian-Eulerian (EE two-fluid) model based on the kinetic theory of granular flow is the most widely used CFD model for cuttings transport.[154,166,201–204] LE computations when implemented are often transient, whereas, EE methods are either done in steady or transient flow conditions.
- Microscopic effects (smaller turbulent length and time scales) are usually not emphasized in CFD models; the models herein have focused on but rather macroscopic flow effects. Reasonably accurate representations of experimental findings are still achievable.[41,62,63,167]

- Flow geometry and system properties employed are usually an adaption from experimental measurements. However, it has been shown through rigorous CFD simulations that a helicoidal cleaning tool attached to the drill pipe aids cuttings transport.[156]
- Uniformly sized particles have been mostly applied. The effect of particle size distribution (using the Rosin-Rammler model or an equivalent) has been rarely studied.[205]
- The finite volume based Ansys Fluent software is the most applied in CFD studies. In-house and open-source codes of similar computational capability but with a less-friendly user environment have also been designed for solving CFD problems.
- Larsen's model[120] has been readily applied for the conversion of ROP (reported in some experiments) to cuttings inlet velocity – a required boundary condition for CFD simulations. The scarcity of the cuttings inlet velocity is a factor that limits experimental validation of CFD models. Busch et al.[91] presented a benchmarking procedure for cuttings transport studies and provided a set of parameters that must be reported in experimental and modelling studies. It is expected that such procedures will enhance industrial applicability of developed models and the accompanying findings/results.
- The application of 4-way coupling with key concentration on particle-particle interactions using DEM contact models coupled with a CFD solver is still emerging.[119,199,206]
- Particle sizes modelled range from a few microns to 10 mm.[63]
- CFD studies that account for cuttings transport with air or other gases are very scarce. The work of Hajidavalloo[207] is the main contribution in this regard.
- Compared to tetrahedral meshes, structured hexahedral meshing is the predominantly applied meshing style in most CFD studies.[41,208–210] This may be attributed to the nature of the annular geometry; thus reducing the risk of unstable and diverging simulations.
- The few CFD-DEM studies that exist on cuttings transport often recommend a particle tracking timestep, which is 100 times smaller than the fluid flow timestep in transient calculations.[119,211] This often results in long computational times. An assessment of computations done with somewhat similar timesteps for both phases in comparison to this recommendation may be worthwhile.
- Volume averaged analyses of key parameters (such as cuttings velocity, and cuttings concentration) over the entire annular domain is often utilized in most CFD studies. However, positional variation in of flow properties along the wellbore geometry (Fig. 13) is necessary for understanding geometrical effects on cuttings transport efficiency.

Figure 13: Positional distribution of cuttings annular concentration.[42,212]

5.0 Tools and Software

Numerous software packages have been developed by key oil and gas service companies for the simulation, monitoring and control of the different aspects of the drilling process. Max3Di™, MaxActivity^{TM}, MaxBHA^{TM} and MaxDrill^{TM} have the developed by Halliburton for drilling optimisation, monitoring drill floor activities, designing the bottomhole assembly and estimating the drill bit efficiency respectively. More recently, they developed DrillingXpert^{TM} as platform for designing an entire drilling system in a single advanced software package. Drillbench^{TM} by Schlumberger is capable of performing dynamic simulations for wellbore pressure control, well control, blowout control during managed and underbalanced operations. It is capable of integrating PETREL's^{TM} trajectory planning module within its interface. Techlog^{TM} another Schlumberger software can be interfaced with Drillbench^{TM} for pore and fracture pressure analysis, thus facilitating a unified modelling interface. These packages have been largely applied in different projects with remarkable benefits (drilling cost and time savings) achieved. OLGA^{TM}, a transient multiphase flow simulator by Schlumberger may also be applied to simulate the multiphase conditions during drilling mud circulation. Pegasus-Vertex, DrillScan and OLIASOFT are other emerging companies with a variety of software packages for modelling torque and drag, drilling hydraulics and trajectory design.

The approach from the academia to studying pressure control during MPD and conventional drilling applications has focused on the development of first principles and lower order models (made up of PDEs, ODEs and AEs, which are sometimes configured within a user interface), for which solutions are coded in platforms like MATLAB® and C++.[81] This may be attributed to the fact that most commercial blackbox software (with little or no allowance for modification of the source codes) are not readily adaptable to the explorative research activities in the academia. Expensive licensing costs (when academic software versions are unavailable) may also be attributed to the infrequent usage of these highly sophisticated commercial packages. Asides, the research-friendly SINTEF drilling hydraulic model, the IRIS drilling simulator (WeMod) has been applied for studying process control-related concepts as in many research contributions.[31,32]

The fluid dynamics community has witnessed the development of commercial software packages such as ANSYS Fluent^{TM}, ANSYS CFX^{TM}, Star CCM+^{TM}, (mainly for cuttings transport and drilling mud analyses) with ANSYS Fluent being the predominantly applied software in CFD related studies. Other open source codes such as Gerris^{TM}, OpenFOAM^{TM}, SU2 code^{TM} and Simscale^{TM} have also gained popularity. Pre-processing, visualisation and post processing of CFD results are also paramount for successful interpretation of computations and have been carried out suing software like GAMBIT^{TM}, AUTOCAD^{TM}, SpaceClaim^{TM} and Paraview^{TM} respectively. Recent studies that couple CFD computations with DEM models for detailed resolution of particle contacts, have applied EDEM^{TM} and LIGGGHTS^{TM}.

6.0 Integrated application of control (PSE-based) and fluid dynamics (CFD-based) perspectives for sustainable operations

It is evident from the discussion so far that process control and optimisation studies have largely simplified or ignored key phenomena such as the effects of cuttings/particle modulation on the fluid flow profile and wellbore pressure. Similarly, cuttings transport studies have neglected the need for real time monitoring, automation and control of drilling parameters such as downhole pressure. Although some of the developed mechanistic models account for downhole pressure variation as a function the mud flowrate and other key parameters, the fast-paced dynamics of drilling operations requires frequent calibration using field data for their industrial applicability. Hence, an integrated approach (PSE+CFD) will be desirable for drilling operations. Despite the pronounced difficulty such an attempt may require, Cayeux and co-workers[213–215] have attempted such integration for real time applications.

A cuttings transport model was developed to monitor two separate drilling (conventional and MPD) operations in the North Sea. Unknown parameters such as the cuttings size were calibrated to yield a good match with topside measurement such as the slurry flow rate.[213] This enabled precise identification of cuttings bed locations along the wells, and the adjustment of drilling parameters (operational recommendations) for bed removal. A real time operation support tool developed by Cayeux and Daireaux[215], enabled automatic friction monitoring with the capability of triggering alarms when severe downhole deterioration was detected. The system's online interpretation of large amounts of drilling data aided this early recognition of downhole problems; this was also demonstrated in a similar work of theirs in a North Sea well.[214] Warnings that indicated poor hole cleaning emerged; thus guiding the operator's decisions on cleaning the wellbore (after stopping the drilling operation) or continuing the drilling process. A similar contribution by Frangos[216] involved the development of a statistical-based approach (ensemble Kalman filtering) for the prediction and monitoring of the location and extent of cuttings build-up along a wellbore. Their model is able to capture the dominant characteristics of the cuttings transport process while incorporating process disturbances and uncertainties in real time field measurements. Salminen et al.[217] developed a real-time method for predicting impending stuck pipe with sufficient warning for its prevention. Their method implements a hydraulic model, real-time and historical data and some data analytics techniques for predicting the risk of a stuck pipe. They demonstrated early prediction of stuck pipe incidents; thus allowing preventive measures to be taken. No false alarms were observed using their proposed approach.

It is worth emphasizing that similar drilling problems in field operations do not necessarily present themselves with the same pattern of symptoms. Hence, the detection of abnormal drilling conditions depends on rigorous analysis of multiple symptoms (e.g. abnormal rise in friction factor) if safety must be maintained.[213] These analyses in turn require the application of specialised tools, which must be used in an integrated manner. As research in both fields continues to advance, better integration methodologies for sustainable operations should be sought after.

7.0 Open problems and research opportunities

The advancements in drilling simulation, control and experimentation have some unaddressed challenges that pave way for potential research opportunities:

- Despite several sophisticated developments of drilling simulators in the oil and gas industry, they have hardly penetrated the realm of academic research. Collaborations in this regard hold great potential for fruitful improvements in drilling software. More efforts are needed towards a unification of the functionalities of separate software for providing robust solutions to drilling challenges.
- Cementing and completion operations, which require efficient displacement of the drilling mud is an area requiring more research attention[218,219]. This is because downhole rheological control (maintain the correct rheological hierarchy) of the cement slurry, spacer fluid and the drilling mud significantly affects the stability of the displacement process. Blowout events have often been attributed to hydrocarbon leakage due to poor cementing jobs.
- More studies are needed on the use of multiple nanoparticle types in drilling fluid formulations. High temperature and pressure experimental studies are required to full ascertain drilling fluid rheological behaviour under harsh downhole conditions. Novel quantitative techniques (such as Nuclear Magnetic Resonance) for the evaluation of formation damage and potential fluid loss are also required. More experimental and numerical assessments on the stability of supercritical CO_2 for MPD operations are required.
- There is a growing need for downhole data quality improvement via wired drillpipe (WDP) and mud pulse telemetry systems. Poorly calibrated sensors, data transmission errors, and abnormal wellbore conditions are some reasons for bad data.[220] Hence, the developments of corrective data processing techniques and noise filtering techniques would greatly facilitate modelling efforts. Methods to determining unmeasurable model parameters and differentiating accurate from inaccurate data points are also needed. Furthermore, the details of signal modulation, data compression and surface noise cancellation techniques are mostly not clearly described in the few available journals or sometimes kept as company secrets;[83] more work is needed on the elucidation of high bandwidth electromagnetic data transmission systems. Low bit rate is a fundamental limitation of some of telemetric systems (especially mud pulse telemetry; 1-2 pulses per second); this causes severe delays (in tens of seconds) between information transmission from the subsurface (downhole) to the surface, thus creating challenges for real-time control. Ingenious solutions and new technologies are required to address this problem.[83]
- A comparative analysis of model performance carried out by Aarsnes et al.[75] against a high fidelity simulator (OLGA) revealed that drift flux models (DFMs) had superior performance to the popularly used ODE models for annular multiphase flow description. The accuracy of DFMs may be further explored with particular emphasis on the adaptation of accurate closure relations to simplified DFM models.

- The desire to replace super challenging models with calibrated simpler models will increase the need for machine learning (AI techniques). These techniques will also be very suitable for proxy model development from numerous simulations of expensive commercial software, which contain high fidelity models. Hence, run time may be significantly reduced for future prediction and optimisation studies. More robust switched control schemes for online usage of high fidelity, reduced order/AI models and real time data wold greatly facilitate the automation of drilling operations.

- Advanced drilling optimisation methodologies are required to determine the optimal ROP while ensuring adequate hole cleaning. While a high ROP is often desired, and indicates good bit performance, the accompanying increase in cuttings influx rate into the wellbore must be compensated for. Optimisation studies will also help clarify ambiguities concerning the use of low-viscosity mud (for promoting turbulence and increased transport efficiency) or the use of medium viscosity muds, which promote better suspension.

- Turbulence modelling is still a challenging topic in the field of fluid dynamics. Although several advancements have been made in describing turbulence in single phase flows, more work is still required for multiphase flows (especially those involving particles). In this age of big data, the combination of machine learning and turbulence modelling (using physics-based and statistical methods) holds great potential for understanding turbulence induced particle motion. This may also be useful for increasing the accuracy and reducing the uncertainty of RANS models implemented in commercial CFD codes used in cuttings transport studies.[221,222]

- More research is needed on the coupling of CFD and DEM methods for understanding the effect of particle collision and fluid dynamics of cuttings transport. However, the accuracy of simulations is dependent on the contact models (Spring-dashpot, Hertzian etc.) and several input parameters of the rock particles (friction coefficients, elasticity properties, Young's modulus, Poisson ratio), which are only obtainable from material calibration studies. Unfortunately, these studies are scarce. The potential for FEM-DEM coupling[223] in describing cuttings transport needs to be further explored. Further advancements in GPU architecture are required for these time consuming calculations.[224]

- UBD operations with numerous phases: gas/oil/water influx, drilling mud, solid cuttings, has hardly been modelled via CFD methods.[119,206] Detailed evaluation on the impacts of fluid influx on cuttings transport efficiency is indeed worth investigating.

- More clarity is needed on the stopping criteria for transient simulations of cuttings transport. Although the attainment of statistically stationary state (with fully developed flowing conditions), is a theoretically reasonable stopping criteria, most studies do not provide explanations on this concept when setting up their simulations. Hence, the accuracy of obtained results becomes difficult to ascertain. CFD modelling frameworks that provide guidance on the choice of computational settings (time-step size, under-relaxation factors, courant number etc.) for different flow conditions are needed.

- Comparative benchmarking studies (via experimental validation) on the use of different CFD softwares is necessary for ascertaining their limitations in modelling several aspects (turbulence, particle deposition, particle tracking and fluid-particle coupling) of cuttings transport phenomena. Furthermore, studies that compare the accuracy of Eulerian-Eulerian and Lagrangian-Eulerian methods for modelling cuttings transport at different particle concentrations are needed.
- Most CFD studies pertaining to cuttings transport have hardly analysed flow behaviour around bends or with a tortuous wellbore. The effect of particle shape has also been hardly been considered experimentally and numerically. An important factor to consider here will be the particle size to mesh size ratio especially with highly nonspherical particles. The consideration of the smallest cell size (in a mesh) being large enough to contain each particle in the EE framework still needs clarification; given the fact that cuttings encountered during drilling may be as large as 10 mm. Is such a system beyond the capabilities of the EE modelling approach?
- Polydispersed particle systems with the aid of a size distribution model have not been widely considered. Furthermore, industrial sand is the most applied type of solid in experimental campaigns. However, various rock types are encountered during drilling.
- Mechanistic and semi-empirical models hardly consider the effects of turbulence fluctuating velocity on the efficiency of cuttings bed removal.[225] Hence, this prevalent assumption of ignoring the effect of flow turbulence on bed erosion needs to be addressed. Furthermore, the effect of fluid rheology on the drag and lift forces if incorporated, is also expected to improve the accuracy of these models. More advanced multi-particle velocity measurement techniques (e.g. particle image velocimetry) in highly turbulent flows are needed for extensive validation of these models.
- Future modelling efforts need to incorporate the effects of downhole uncertainty. Increased economic potential from model-based decisions drilling require the consideration of complicated uncertain downhole events.
- The development of additional robust closure relations from experiments or direct numerical simulations will hugely aid two-fluid Eulerian-Eulerian models. The application of stochastic particle collision models based on the Enskog Simulation Monte Carlo approach will be useful for dense particulate flow modelling using the LE approach.[199]
- Although the effect of drillpipe rotation on cuttings transport has been widely considered, the impact of drillpipe reciprocating motion requires more experimentation and modeling research

contributions. A combination of rotary and reciprocating motion is expected to better represent the drillpipe motion.

- 1D and 2D mechanistic models require improvements in correlations for the friction factor, drag coefficient, shear stress between different interfaces, particle deposition and entrainment rates. Thus enhancing the reliability of particle deposition predictions along the entire wellbore profile. Highly accurate models are also required for the determination of the wiper trip speed especially during coiled tubing cleaning operations.
- The development of benchmarking case studies to assess the performance of open source and commercial codes/software is essential.[9] This would be further facilitated by the availability of open source (sharable and expandable) data sets for model performance evaluation.
- Dispersed multiphase (gas-liquid and liquid-liquid) flows in open and closed channels, free surface flows and segregated flows constitute challenging fields (with unresolved problems) which have received tremendous attention from the chemical engineering community over the past decades. Sophisticated fluid dynamics techniques have often been applied to model flows with such complexity for industrial applications such as diary production and spray drying. The modelling advancements developed for the description of such phenomena could be further extended to particulate flow systems in petroleum engineering. Particularly, the Ergun[226] equation developed for fluidized beds (in reactors, absorber columns and other chemical process equipment) has been readily applied for the description of cuttings transport phenomena. The development of a mechanistic model for the prediction of the drag coefficient of a nonspherical particle in a non-newtonian fluid is open research question in chemical engineering. Developments in this area will definitely increase the accuracy of cuttings transport and deposition predictions during drilling in the petroleum industry.

8.0 Conclusions

In this article, we have expounded on the necessity for drilling modelling, control and automation in oil and gas development, based on an overview of existing research contributions; important challenges and research opportunities have been identified. Although the process control community has tremendously advanced the field of managed pressure drilling using, sophisticated control schemes, the fluid dynamics community has majorly addressed the modelling of wellbore cleaning operations. We believe that future research endeavours will progress towards a seamless integration of both perspectives. The application of artificial intelligence techniques to the drilling industry is expected to increase in the near future, as these computationally intelligent methods hold promising potential for real time decision support. Amongst several other opportunities highlighted herein, it is expected that GPU-based computations will gain increasing acceptance; their computational efficiency compared to conventional CPU computations on several processing cores has been widely demonstrated; thus allowing quicker insights into important phenomena. The need for model calibration during pressure control and cuttings transport has been strongly emphasized in this paper, if developed models must maintain industrial relevance. With increasing discoveries of oil and gas fields in highly challenging locations, drilling operations are commensurately expected to be complicated; scientists and engineers must be equipped with the current state of the art (described herein), if novel, innovative, environmentally friendly, economic and safe drilling methods must be developed.

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Nomenclature

AT: Acoustic Telemetry

AE: Algebraic Equation

AI: Artificial Intelligence

ANN: Artificial Neural Network

BHA: Bottomhole Assembly

BHP: Bottomhole Pressure

BOP: Blowout Preventer

BP: Bingham Plastic (Rheology)

BP: British Petroleum (Company)

CFD: Computational Fluid Dynamics

DFM: Drift flux Model

DAPC: Dynamic Annular Pressure Control

DP: Dynamic Programming

DMD: Dynamic Model Decomposition

DMDc: Dynamic Mode Decomposition with control

EE: Eulerian-Eulerian

EnKF: Ensemble Kalman Filters

FEM: Finite Element Method

GA: Genetic Algorithm

HB: Herschel Bulkley

KOP: Kick-off Point

LE: Lagrangian-Eulerian

LOL: Lumped Order Lower Models

MPD: Managed Pressure Drilling

MD: Measured Depth

MPC: Model Predictive Control

MPT: Mud Pulse Telemetry

MSE: Mechanical Specific Energy

NMPC: Nonlinear Model Predictive Control

OBM: Oil Base Mud

ODE: Ordinary Differential Equation

OLGA: Oil and Gas Simulator

PDE: Partial Differential Equations

PL: Power Law

POD: Proper Orthogonal Decomposition

PSE: Process Systems Engineering

QDMC: Quadratic-Dynamic Matric Controller

RANS: Reynolds Averaged Navier Stokes

RSME: Root Mean Square Error

ROP: Rate of Penetration

SCCO2: Supercritical carbon dioxide

SETS: Stability Enhancing Two-Step

SIMPLE: Semi-Implicit Method for Pressure-Linked Equations

SPE/IADC: Society of Petroleum Engineers/International Association of Drilling Contractors

SVM: Support Vector Machines

TVD: True Vertical Depth

UBD: Underbalanced Drilling

WBM: Water Base Mud

WCTT: wired coiled tubing telemetry

WDPT: Wired Drillpipe Telemetry

WET: Wireless Electromagnetic Telemetry

WOB: Weight on Bit

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Table 1: A comparative performance of LWD telemetry technologies[83]

Features	LWD telemetry technology			
	Electromagnetic	Acoustics	Mud pulses	Wired Drill pipe
Maximum transmission data range (bps)	10	20	20	57600
Maximum depth (m)	5500	3700	12200	Unlimited
Data quantity	Medium	Low	High	Very high
Signal attenuation	High	High	Medium	N/A
Signal interference	High	Medium	medium	low
Installation and other cost	Medium	Medium	Low	High

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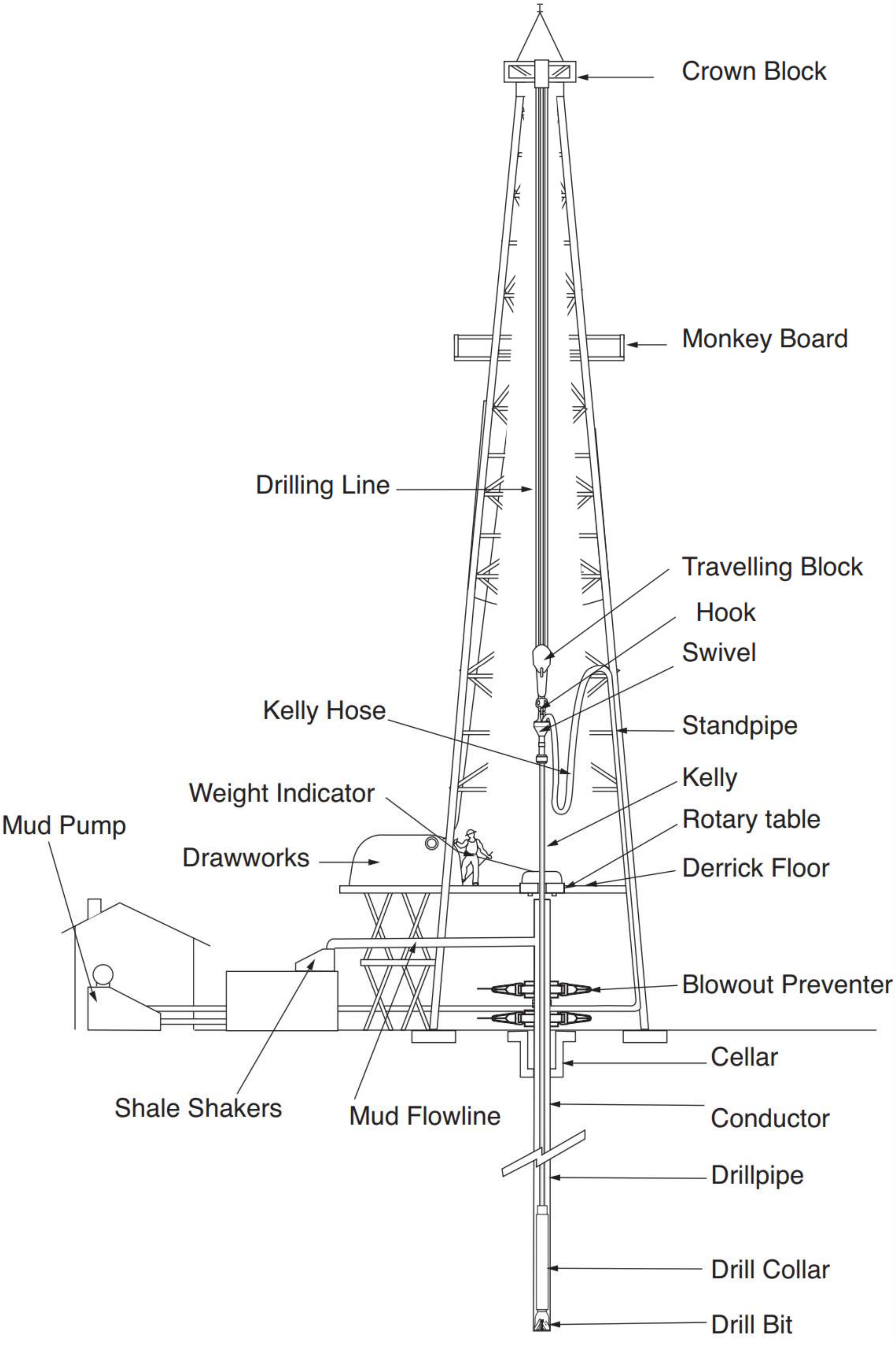


Figure 1: Components of a typical drilling system.[15]

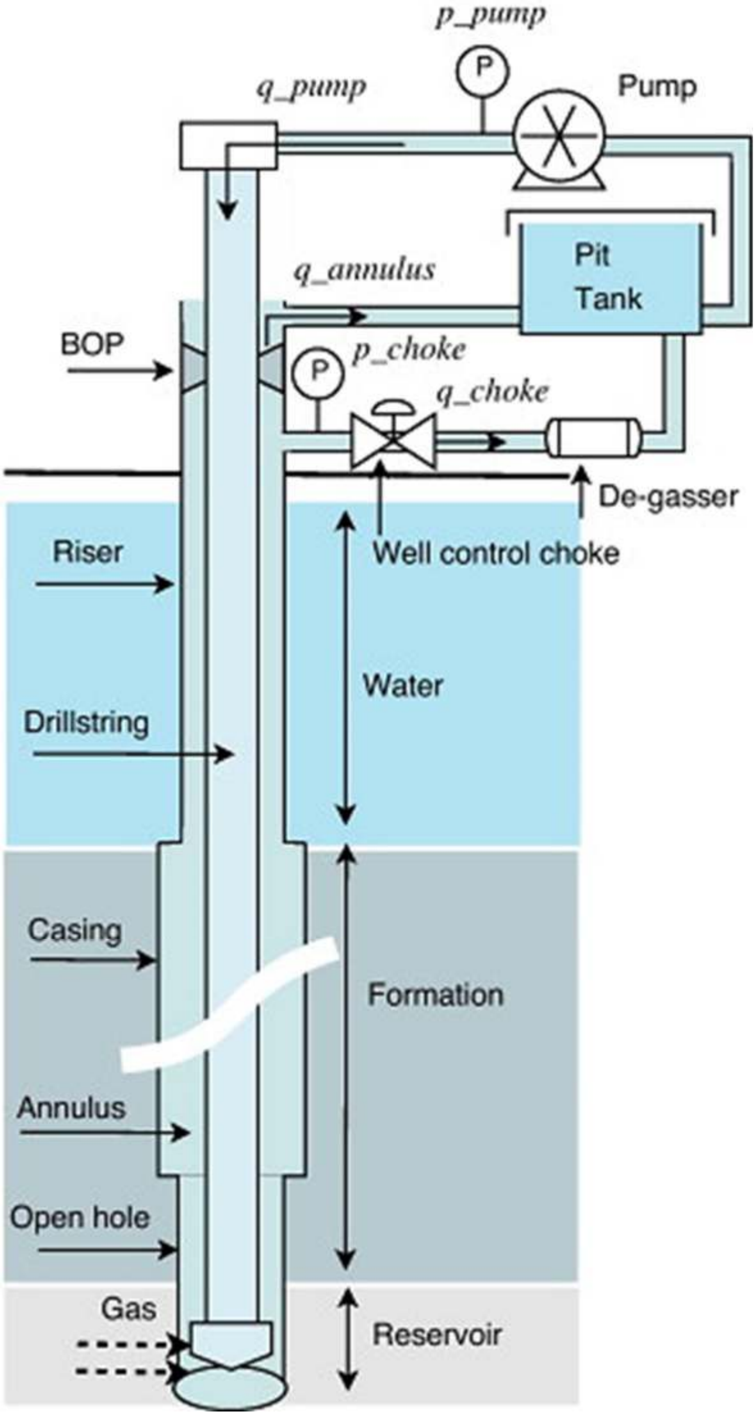
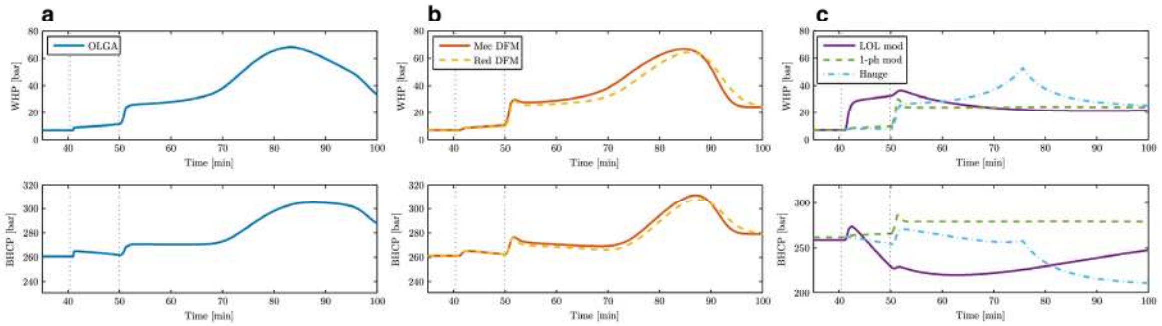
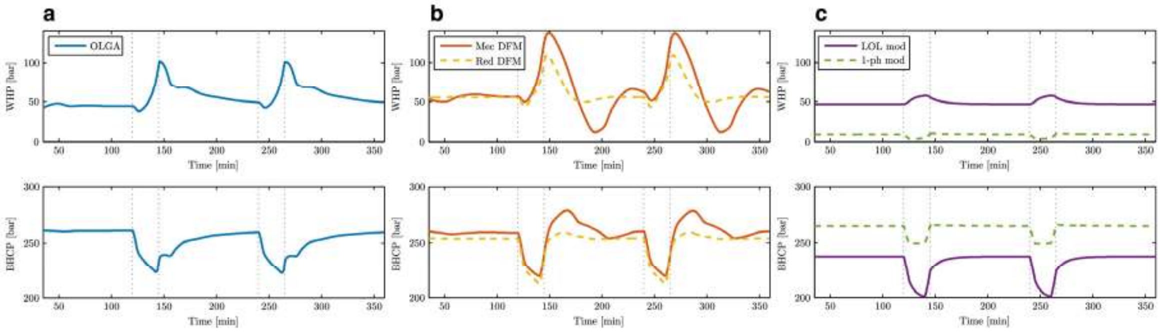


Figure 2: A managed pressure drilling system showing unwanted gas influx from the reservoir.[11]

(i) MPD gas kick



(ii) UBD connections



(iii) UBD operating envelope

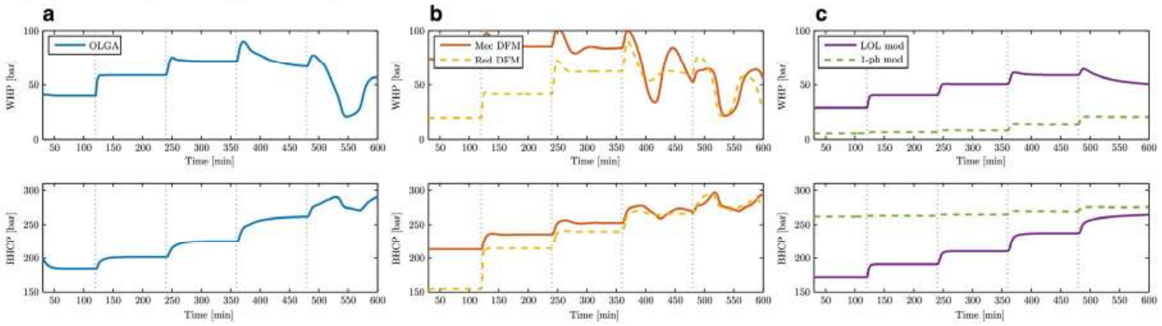


Figure 3: Bottomhole pressure and wellhead pressure trends for three operational scenarios and the evaluation of lower order models (mechanistic and reduced Drift Flux Models, 1-phase model, Hauge et al.[36] model and the low order lumped model) in comparison with a high fidelity multiphase flow simulator OLGA.[75]

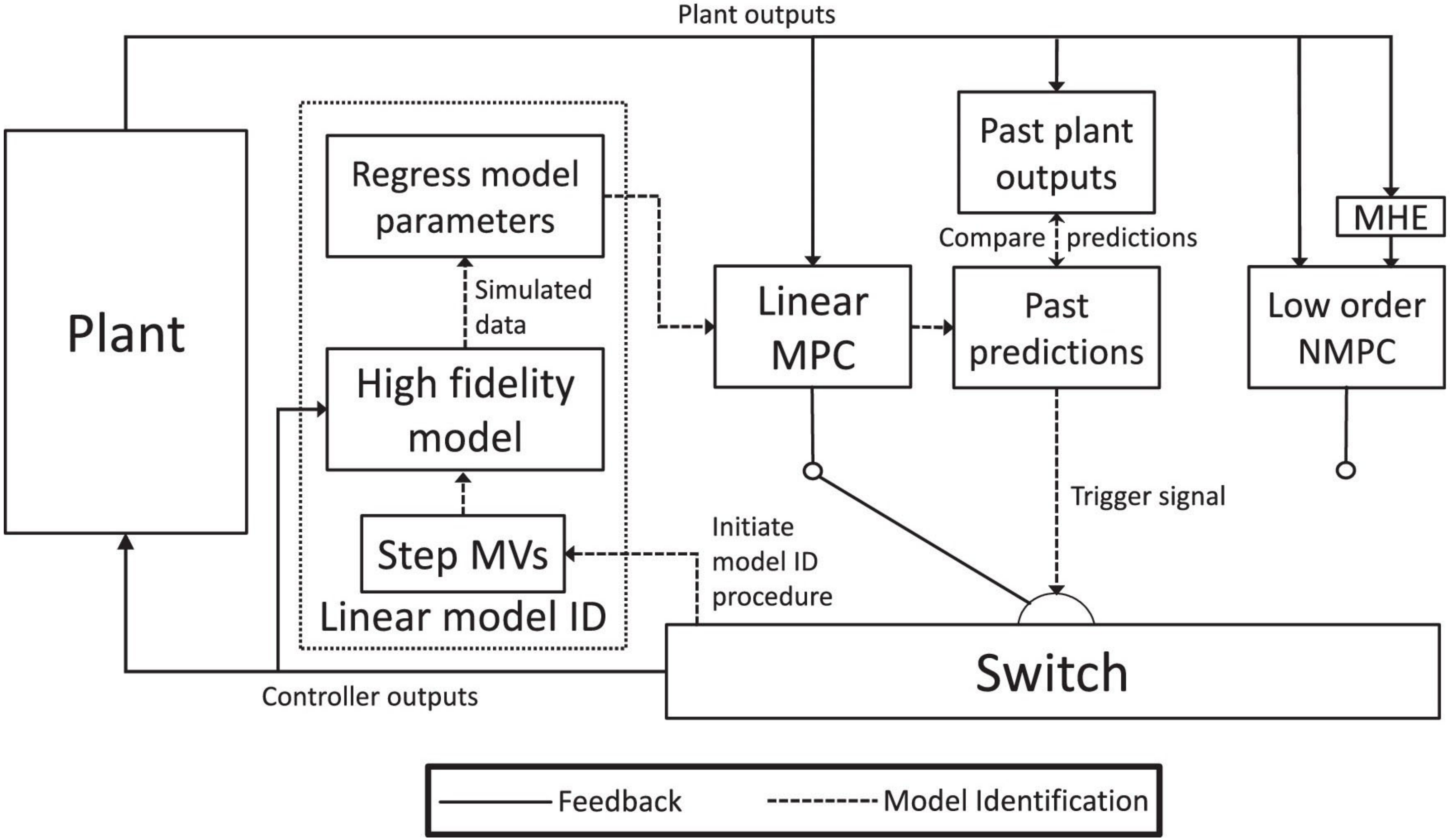


Figure 4: Diagram of a switched control system.[14]

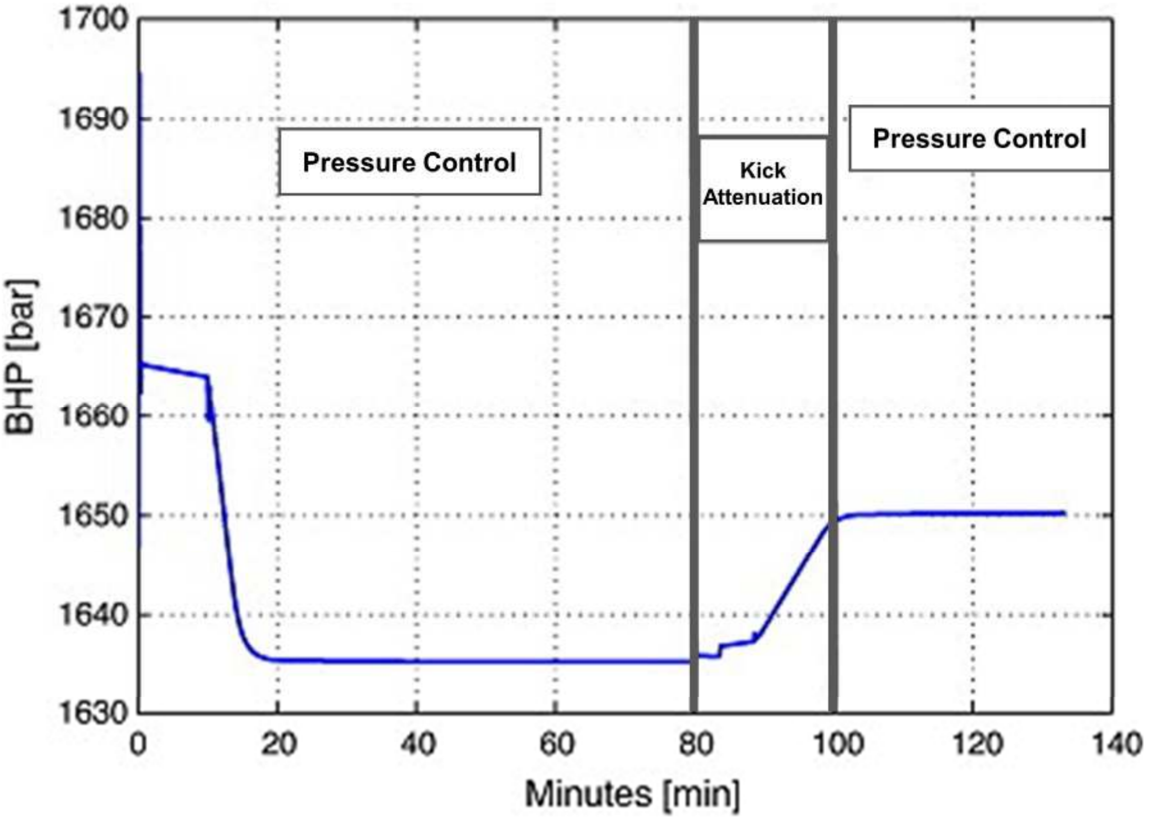


Figure 5: Bottomhole pressure control during a kick at 80 mins.[93]

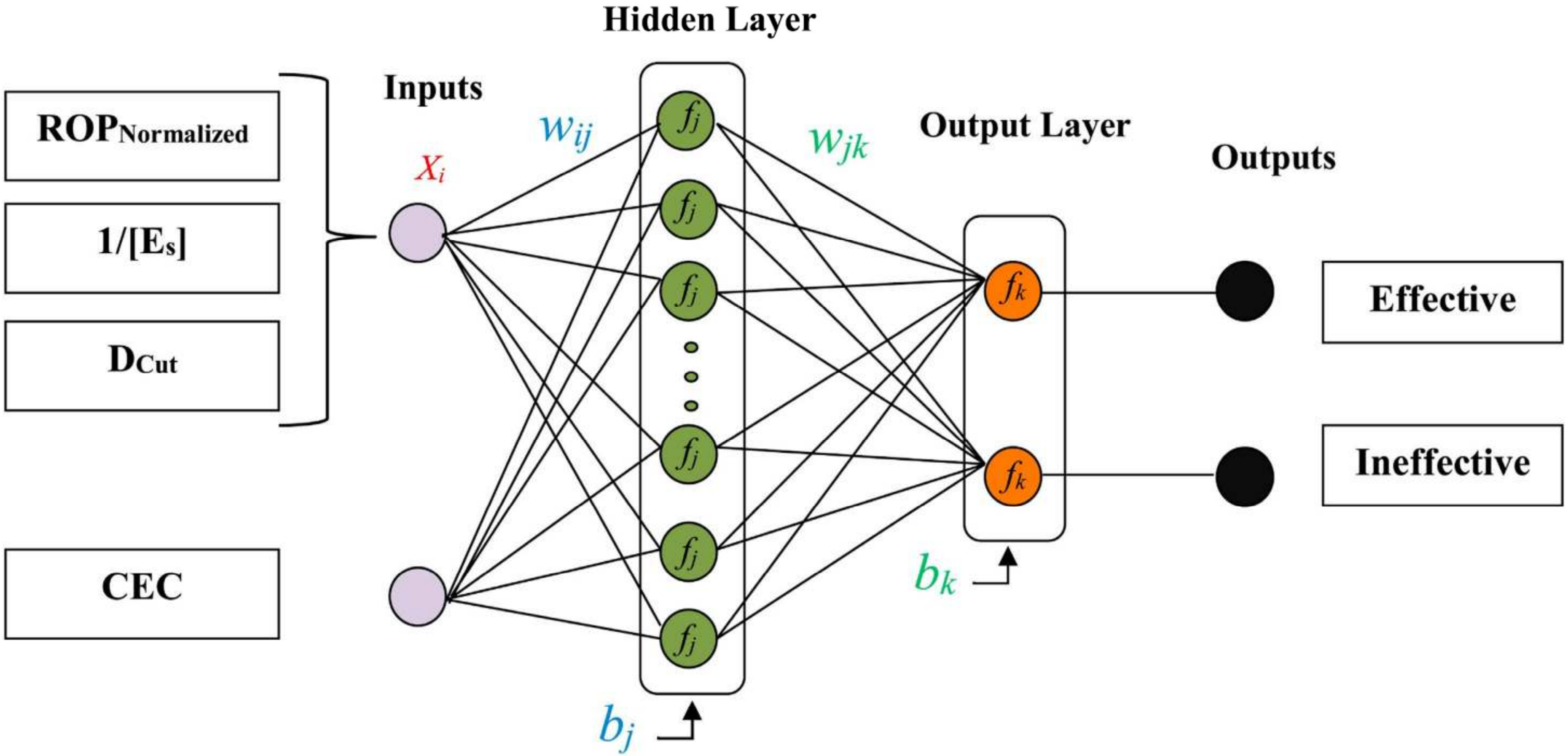


Figure 6: Schematic structure of a pattern recognition network.[109]

Gas: air, natural gas, exhaust gas, combustion gas	Fresh water	Oil: diesel or crude
Mist: Droplets of water or mud carried in the air stream **Foam:** Air bubbles surrounded by a film of water containing foam-stabilizing surfactant **Stable foam:** Foam containing film-strengthening materials, such as organic polymers and bentonite	**Solution:** True and colloidal, i.e., solids do not separate from water on prolonged standing **Solids in solution with water include:** ☐ Salts, e.g., sodium chloride, calcium chloride ☐ Surfactants, e.g., detergents, flocculants ☐ Organic colloids, e.g., cellulosic and acrylic polymers **Emulsions:** Oily liquid maintained in small droplets in water by an emulsifying agent, e.g., diesel oil and film stabilising surfactant **Mud:** Suspension of solids (e.g., clay, barite) in water with chemical additives for property modification	**Oil mud:** A stable oil-base drilling fluid contains: ☐ Water-emulsifying agents ☐ Suspending agents ☐ Filtration-control agents containing cuttings from the formation drilled ☐ May contain Barite to raise the density

Figure 7: Classification of drilling fluids according to their principal constituent.[9]

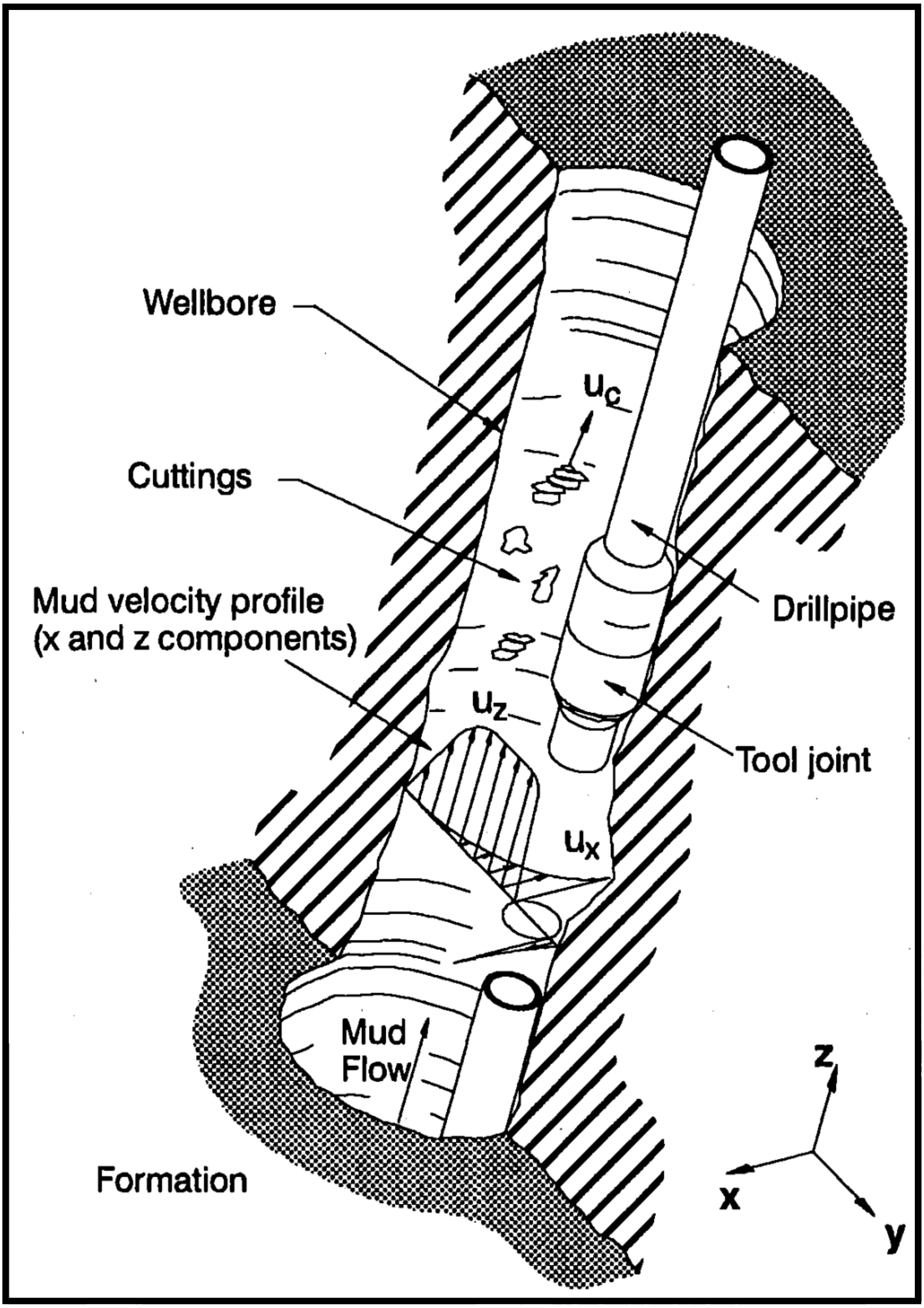


Figure 8: Particle transport in the presence of a mainstream non-Newtonian fluid during drilling operations.[160]

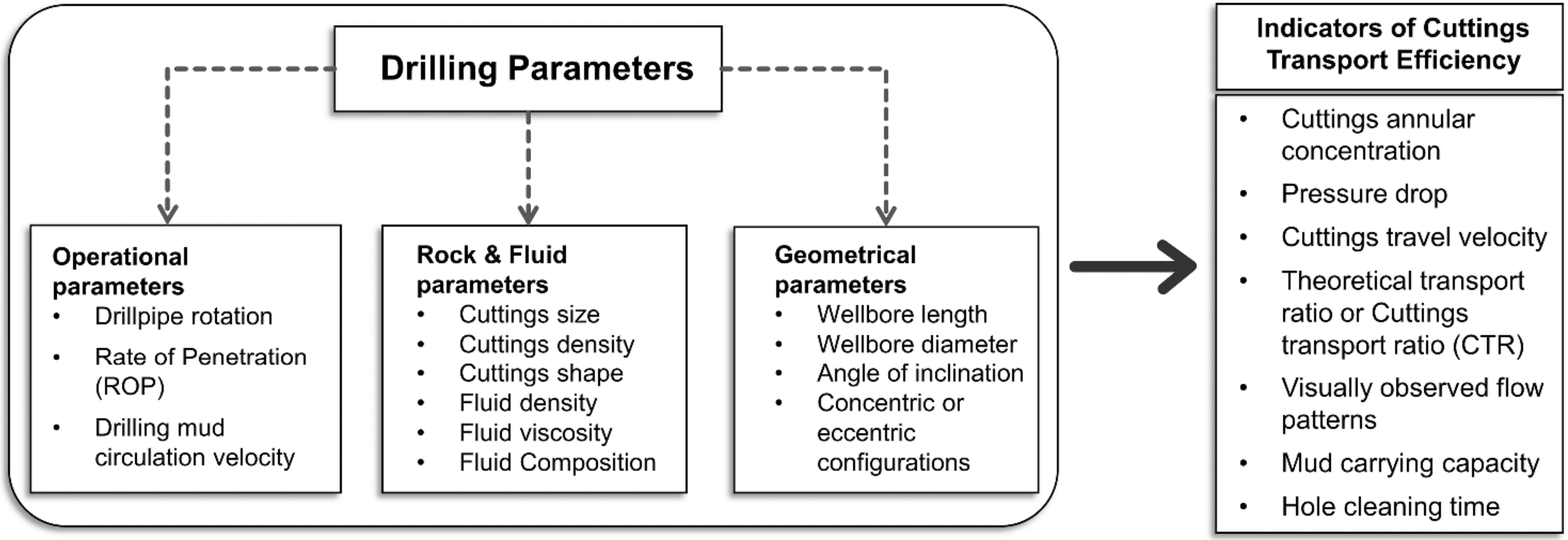


Figure 9: Factors affecting drill cuttings transport efficiency.

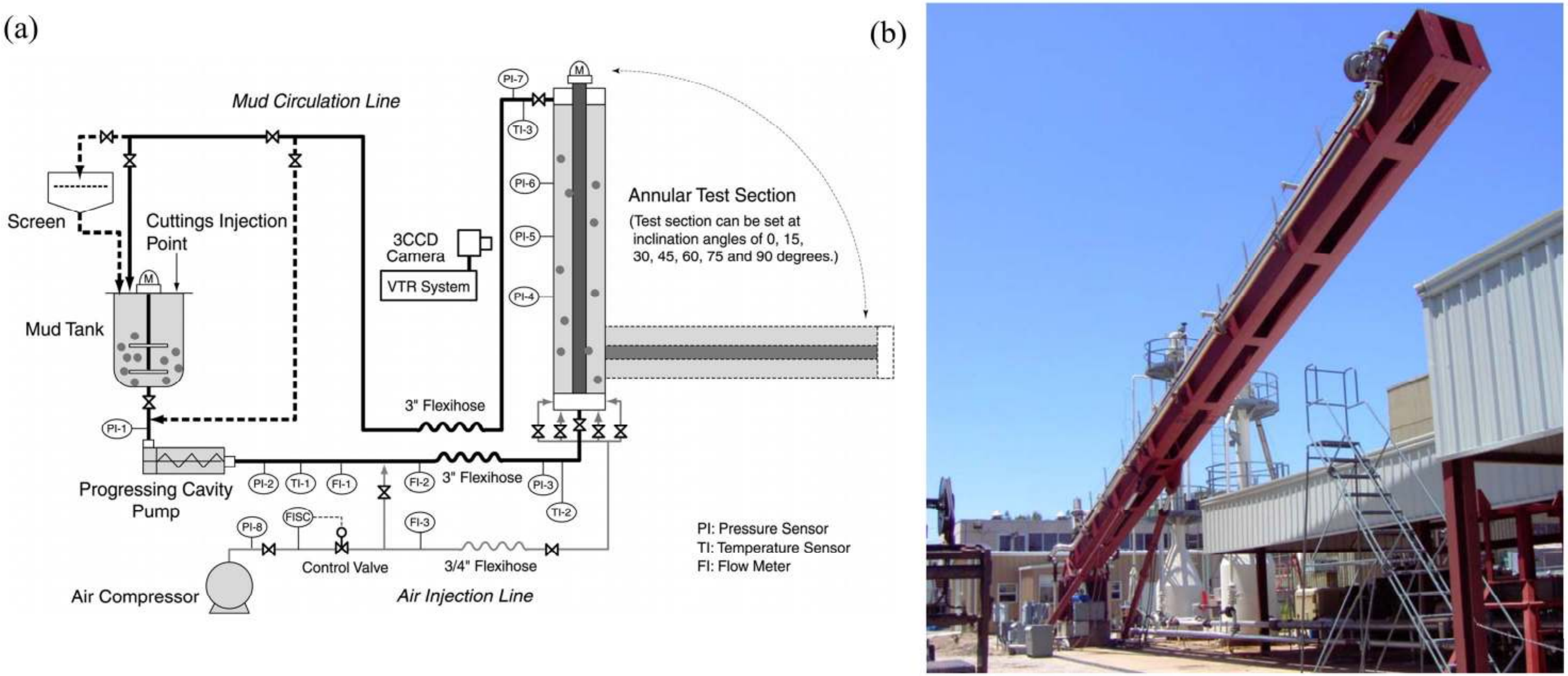


Figure 10: Typical components of an experimental set-up for cuttings transport (a);[180] Experimental testing facility at the University of Tulsa (b).[181]

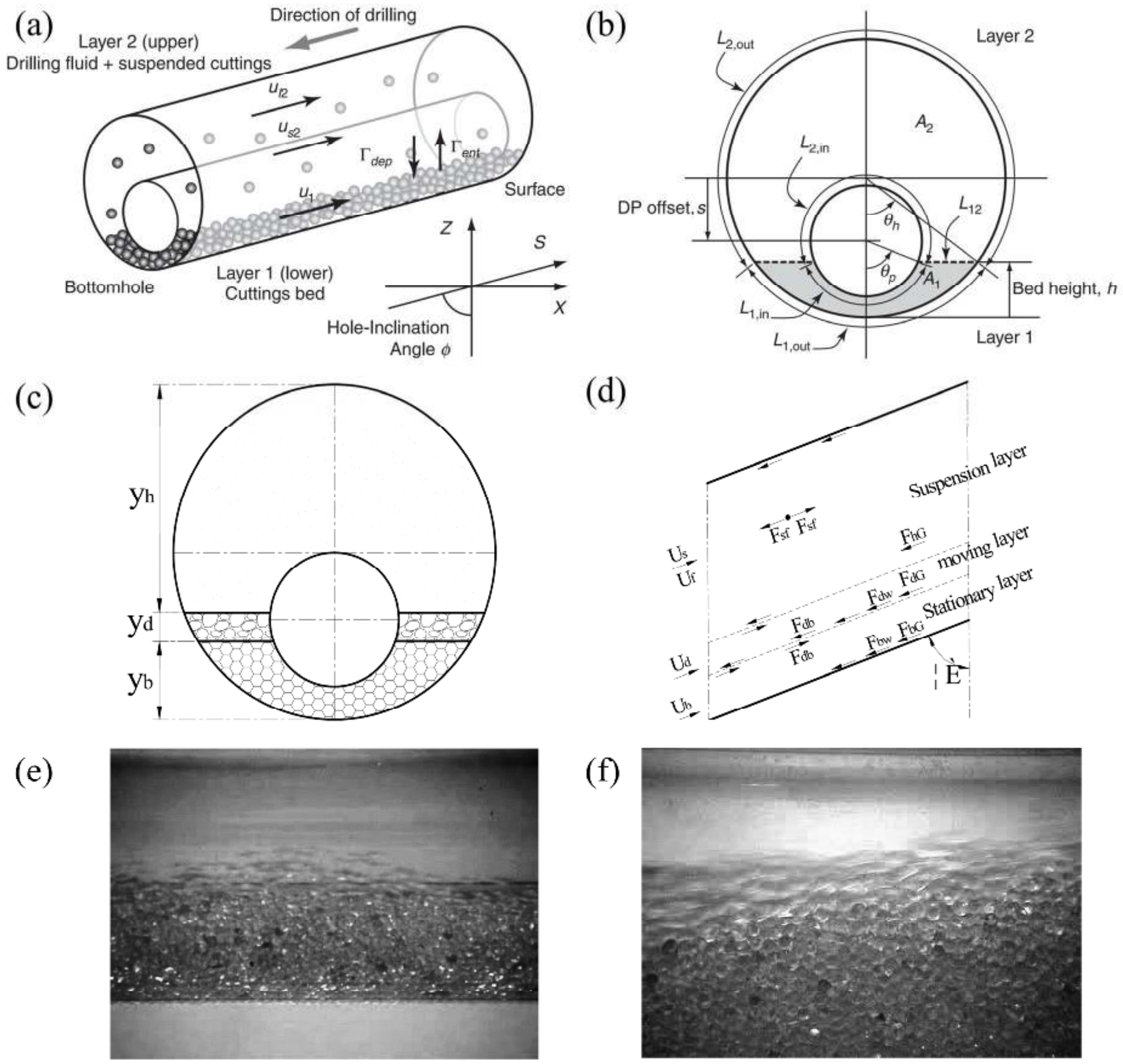


Figure 11: Schematic representation of a 2-layer (a, b, e) and 3-layer (c, d, f) cuttings transport model with corresponding experimental observations (e, f). The 3-layer assumes the existence of a bottom stationary cuttings layer, a moving middle layer and a top suspension layer; whereas the 2-layer model assumes a bottom stationary layer and a top suspension layer.[138,189,190].

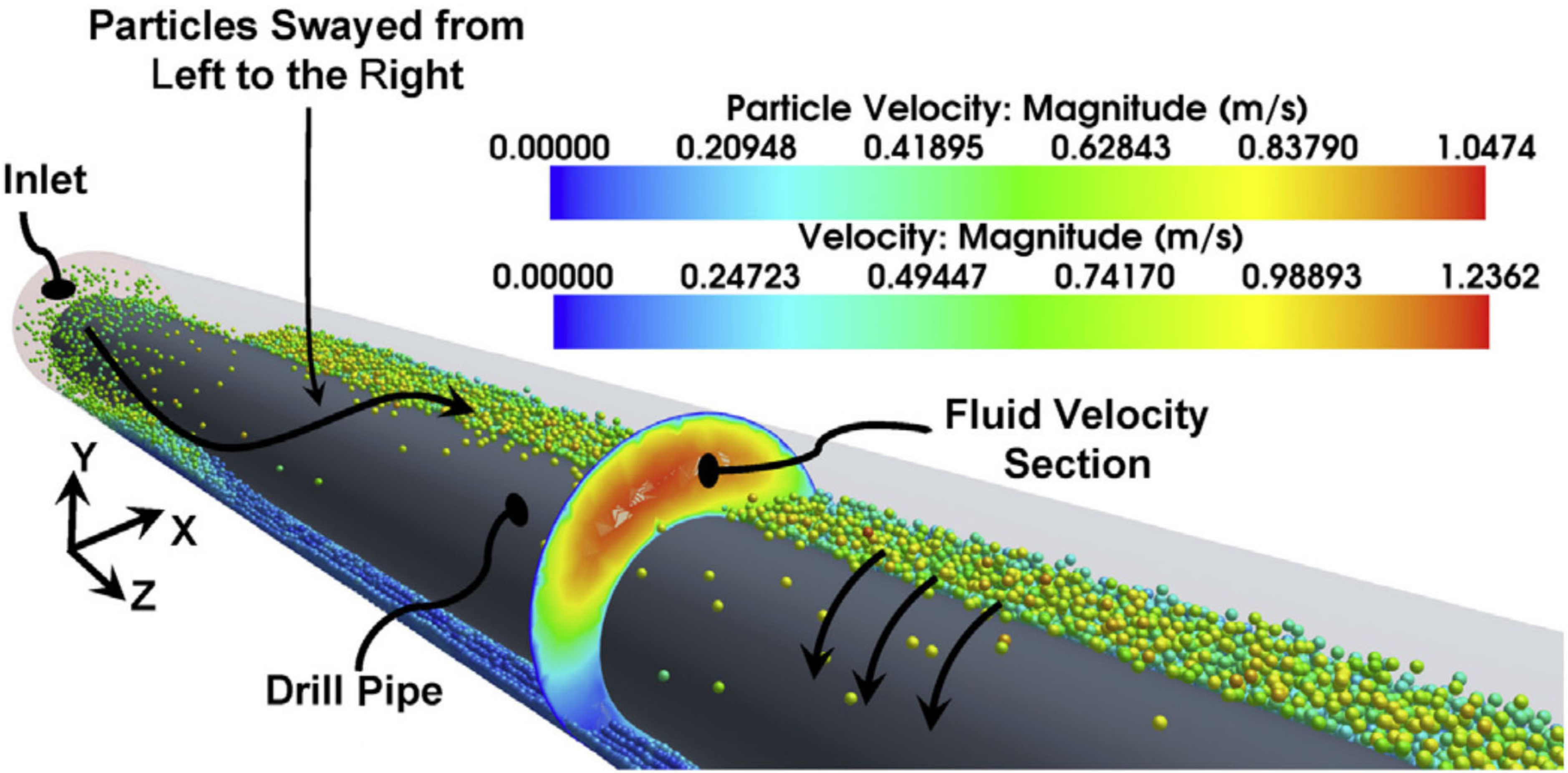


Figure 12: CFD simulation of cuttings transport in a horizontal annular configuration during drilling.[119]

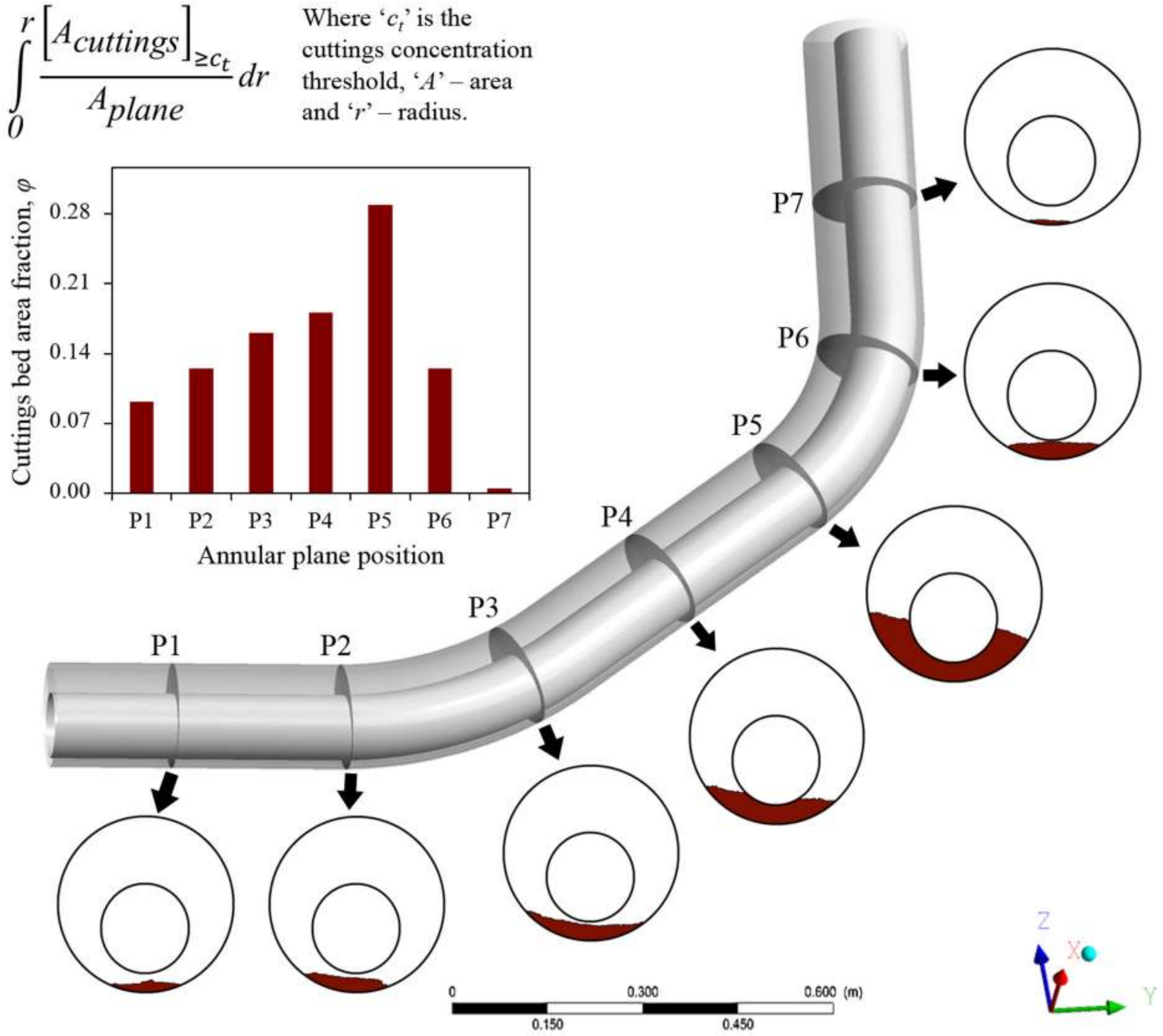


Figure 13: Positional distribution of cuttings annular concentration.[42,212]