Review Paper

Kick detection and remedial action in managed pressure drilling: a review

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Abstract

Increasing the global demand for natural resources directs the oil industries to explore in geologically challenging structures and offshore reserves. Oil industries are always searching for innovative drilling technologies to optimize field development process in a complex structure. Managed pressure drilling (MPD) is now becoming an attractive alternative to the traditional overbalance drilling in complex formation. MPD offered substantial benefits in terms of project economics and reduced non-productive time (NPT). These benefits are substantial in the offshore structure, where any downtime significantly impacts the project cost. MPD is designed to avoid continuous formation influx into the wellbore, and any incidental fluid is contained with a specific predetermined process. MPD used some specialized tools and techniques to enhance traditional kick detection capabilities and circulate formation influx while keeping NPT at the minimum level. Early kick detection is a primary concern for the drilling industry to ensure the safety of the drilling rig, crews, and environmental protection. This research focused on a systematic review of kick detection and mitigation in MPD operation. A review of recent advancements in MPD, various early kick detection methods, comparative study of different kick indicators with their significance, different gas kick models, and risk analysis are analyzed systemically. Several control methods in the MPD operation are summarized. A systematic comparison of different gas kick circulation methods in conventional drilling and MPD is presented in this study. Also, different alternative responses to conventional kick circulation methods are summarized. This work critically analyzed different kick responses of circulating and non-circulating methods, e.g. shut-in, modified pump shut down, increasing in casing pressure and stepwise increase in pump rate. However, all circulation methods are elementary, and no kick circulation method is universally applicable to all drilling operations. Finally, this review emphasized some recent progress and challenges in kick detection on managed pressure drilling.

Keywords MPD · Early kick detection · Kick response · Well control

List of symbols

λ	Gas void fraction
ϕ	Wave scattering variable
a_g	Speed of sound in gas = 316 m/s
a_l	Speed of sound in liquid = 1500 m/s
C	Sonic velocity
C_A	Annular capacity
C_o	Distribution factor
$C_i,\ C_1,\ C_2,\ C_3$	Coefficient
d	Pipe diameter
f	Friction factor
F_g	Frictional cross section area available to gas
g	Acceleration due to gravity (9.8 m/s^{-2})
h_G	Distance of the bubble head to the of the riser
K	Distribution coefficient
M_G	Mass of the gas bubble (kg)
$MW_{surface}$	Mud weight at surface
P_G	Pressure in the gas bubble (psi)

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P_{pump}	Pump flow rate
P_{go}	Initial average gas pressure (psi)
P_s	Surface pressure (psi)
P_{csi}	Shut in casing pressure (psi)
P_{BHP}	Botthomhole pressure (psi)
$\Delta P_{Hydrostatic}$	Hydrostatic pressure drop (psi)
$\Delta P_{Friction}$	Frictional pressure drop (psi)
P_{choke}	Choke pressure (psi)
Q_l	Liquid rate (bbl/min)
Q_g	Gas rate (scf/min)
Q_{in}	Mud inflow rate
Q_{out}	Mud outflow rate
Q_{pump}	Pump flow rate
S	Distribution coefficient
t	Time (s)
V_f	Filtrate loss volume (bbl)
v_G	Velocity of the gas bubble head (ft/s)
V_{go}	Injected volume of gas (scf)
V_m	Mud volume (bbl)
V_{mud}	Mud volume
$V_{borehole}$	Borehole volume
V_w	Well volume (bbl or cubic ft)
v_m	Mud velocity (ft/s)
V_c	Circulated fluid volume (bbl)
v_t	Taylor bubble rise velocity (ft/s)
$W_{drillstring}$	Weight of the drill string
X_m	Mud compressibility (1/psi)
z	Spatial coordinate variable
Z	Axial position

Abbreviations

BOP	Blow out preventer
BHP	Bottomhole pressure
CBHP	Constant bottom hole pressure
CFD	Computational fluid dynamics
ECD	Equivalent circulation density
HPHT	High-pressure high-temperature
IADC	International association of drilling contractors
MPD	Managed pressure drilling
MW	Mud weight
MWD	Measurement while drilling
OBM	Oil based mud
ODM	Original drilling mud
PTP	Pressure transfer parameter
RCD	Rotating control device
SBM	Synthetic-based mud
UBD	Underbalanced drilling
WCM	Well control matrix
WHP	Wellhead pressure

1 Introduction

Drilling mud is designed to maintain the wellbore pressure higher than the pore pressure boundary and lower than the fracture pressure boundary to avoid any formation influx into the wellbore. This boundary is known as the drilling window. In conventional drilling, a slightly overbalanced environment is preserved to prevent any formation influx. This overbalance condition is reasonable when an extensive range of pore pressure and fracture pressure is available. However, the applicability of the conventional drilling method is very limited in a complex formation or depleted reservoir due to narrow drilling window. This limitation widens the scope of managed pressure drilling (MPD) for complex geological structures. The concept of MPD derived from the forbear technology underbalanced drilling where minor formation influx deliberately allowed to avoid formation damage. MPD technology utilizes every measurement to avoid continuous formation influx, and any incidental flow is carefully controlled with the appropriate process. The International Association of Drilling Contractors (IADC)'s Underbalanced Operations and Managed Pressure Committee has defined "managed pressure drilling (MPD) is an adaptive drilling process used to 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 pressure profile accordingly." [86].

MPD is a relatively new technology to the petroleum industry but recognized as a proven drilling method in the last 15 years. MPD offers not only reduced non-productive time (NPT) but also enables to drill in the crucial geological formation that previously considered as unreliable with available technology. In recent years, MPD has implemented into the different geological regions, e.g. the Asia Pacific, Middle East, Europe, Gulf of Mexico, Russia, and Africa [4, 11, 14, 26, 29, 75, 144, 159, 185]. MPD is also productively implemented in the HPHT wells [26, 67, 164, 167] and fractured carbonate formation [133]. Field application shows that MPD operation successfully mitigates different drilling problems, e.g. lost circulation [136, 145], wellbore instability [50, 208], stuck pipe [11, 126, 136], wellbore control issue [122] and significantly reduce the non-productive time. MPD process utilizes a set of tools and techniques that mitigate the risk and cost associate with drilling in a narrow pressure window by precisely controlling the annular pressure profile in the wellbore. Failure to maintain the narrow drilling pressure profile often causes a kick.

During any drilling operation, if the bottom hole pressure is less than formation pressure; formation fluid such as gas or any other fluid, may enter the wellbore. This influx of formation fluid invasion into the wellbore is known as a kick. Early detection of a kick is a primary concern for the drilling industry to ensure a safe drilling operation, workers' safety, and environmental protection. A late kick detection may cause an uncontrolled blowout, which leads to a higher risk of injury of drilling personnel, catastrophic to drilling facility, potential loss of well and natural resources as well as adversely impacts on the project economics.

Both lab-scale [30, 110, 112, 165, 189] and field study [74, 80] show different early kick detection methods, risk assessment [113, 158, 202] and mitigation system [210]. The effectiveness of kick management largely depends on the prompt detection of a kick and size of the kick when detected. A manual kick detection system depends on the drilling crew's competence, expertise and data interpretation skills that might be inconsistent and inefficient at different drilling environments. However, an automated kick detection system offers robust control on the equipment, consistent data acquisition and intelligent control and quick response to any incidental situation. Since managed pressure drilling works in a very narrow drilling window, any pressure fluctuation within this narrow margin due to a kick can be quickly detected. Once the kick is detected, MPD can promptly control the well at minimum kick size before it initiates a threat to the well integrity. MPD precisely control the annular pressure while circulating the kick out of the hole without shutting the well.

In MPD operation, well control shows a significant advancement over a conventional system. Traditional well control methods rely on fundamental approaches like pit gain at the surface, pump pressure variation for any incoming kick and 'shut in the well' is the only approach to control a well during an unwanted situation. However, there are several alternative responses available with MPD, such as increasing casing pressure, reviewing the pump rate without shutting the well or controlling the mud return rate with a surface choke, etc. These alternative approaches in MPD significantly reduce the response time to kick, NPT, cost, and most importantly provide a safer drilling operation. In MPD operation, this secure handling of gas kick supported by precise control of the drilling parameters like surface backpressure, bottomhole pressure, mud circulation rate etc. So, a very sophisticated control system is essential in a managed pressure drilling system.

Several field studies [20, 52, 85, 93, 122, 126] show the important aspects of well control in MPD operation. Besides the field studies, researchers also demonstrate several well control studies [19, 45, 69, 83, 100, 115, 129, 130] that describe the MPD kick management and different well control scenarios based on kick behaviour. These studies also focused on the dynamic kick management of a managed pressure drilling system. With a well-defined control system, MPD can effectively circulate the kick out of the hole without shutting the well by adequately adjusting the surface backpressure and maintaining an appropriate fluid circulation rate.

There are numerous studies on various aspects of MPD, such as MPD field application, control mechanism, kick identification, risk analysis, decision tree and kick management system etc. available in the literature. However, a comprehensive review of kick detection and kick response in MPD operation is still missing in the literature. This lacking motivated the authors for a comprehensive review of gas kick, kick detection and kick response in MPD operation. The authors also reviewed different well control methods for a constant bottomhole pressure MPD operation.

This manuscript organized as follows: Sect. 2 covers an overview of MPD technology, MPD variant and MPD operating principles. Section 3 describes a detail about the reason for a kick, early kick warning signs and different kick identification methods. Review of gas kick modelling, simulation, and control system of the MPD are presented in Sect. 4. Section 5 shows the different responses of gas kick, risk evaluation and well control matrix. Section 6 covers a review of some recent advancement in MPD operation, including machine learning, computational fluid dynamics, and list some scopes of the further research area in MPD. Finally, Sect. 7 covers a conclusion of this study.

2 Managed pressure drilling compared with conventional drilling method

Drilling methodologies vary with drilling objectives that largely depend on formation characteristics. In conventional overbalanced drilling, the focus is to avoid formation influx and accomplished by maintaining bottomhole pressure above the formation pressure. As a result, this causes formation damage to some extent and does not mitigate any problems of pressure instability. In MPD, the bottomhole pressure is kept nearly equivalent to the formation pressure. Variable surface backpressure is applied to control bottomhole pressure precisely during drilling and keep it in a static condition. Furthermore, MPD can handle pressure related problems like wellbore instability, differential sticking etc. Table 1 shows a comparative analysis of vital key variables about various drilling methods. In conventional drilling, bottomhole pressure (BHP) is achieved by mud weight (MW) and annular frictional pressure. However, in managed pressure drilling, an additional control parameter called 'backpressure' is applied to control the bottomhole pressure. This 'backpressure'

Table 1 Analysis of different drilling methods

Drilling methods	Minimization and control of			Pressure scenario	BHP control	
	Formation influx	Formation damage	Pressure related problem		During drilling	Static condition
Overbalanced drilling	√	X	X	$P_{BHP} > P_r$	BHP = MW + ECD	BHP = MW
Managed pressure drilling	√	√	√	$P_{BHP} \cong P_r$	BHP = MW + ECD + backpressure	BHP = MW + backpressure

√ yes, X no, *ECD* equivalent circulating density, *MW* mud weight, *BHP* bottomhole pressure

Fig. 1 A hypothetical pore pressure gradient and fracture pressure gradient envelope. Redrawn from Stone and Tian [176]

provides a wide range of pressure control. Thus, wellbore pressure remains steady irrespective of the reservoir conditions [194].

Mathematically bottomhole pressure can be expressed as

$$P_{Reservoir} \cong P_{BHP} = \Delta P_{Hydrostatic} + \Delta P_{Friction} + P_{choke}. \qquad (1)$$

2.1 Managed pressure drilling operating envelope

MPD aims to keep bottomhole pressure within prescribed limits and achieve a narrow annular pressure outline accordingly. This slim pressure envelope is due to the geological structure of the reservoir, especially in the offshore, carbonate rock shows a very narrow pressure window. Figure 1 shows a hypothetical pore pressure gradient versus fracture pressure gradient envelope.

Figure 1 indicates that MPD has a very narrow drilling window that needs to maintain throughout the drilling operation. This narrow window is obtained by controlling wellhead pressure or surface backpressure, drilling mud density and mudflow rate. Generally, drillers set the operational and environmental variables like mud density, mud pump rate, casing pressure and rate of penetration. These pre-set variables keep the wellbore pressure slightly above or at balance or near balance with the bottomhole pore pressure. A precise wellbore pressure control allows a driller to work within the narrow margin of fracture pressure and pore pressure.

2.2 Variants in managed pressure drilling

There are three significant variations available in managed pressure drilling based on operating condition. Table 2 shows major MPD variants with their scopes. Each method has its objective regarding pressure control and influx management. In "Constant Bottomhole Pressure" method, bottomhole pressure is controlled by automatic adjusting the choke to track the pre-defined pressure trajectory. The primary goal of the controller is to eliminate any kick or fluid loss when a fracture gradient is approaching pore pressure [140]. In offshore operations where the return mud does not travel through a large diameter drilling riser, the "Dual Gradient Drilling" method is the right choice. This method reduces the number of casings required in the deep-water marine environment. A mud cap and pressurized mud cap method with a sacrificial fluid are used to manage the mud losses in the highly depleted formation. Among these variants, constant bottomhole pressure drilling (CBHP) is the most common scenario for deep well drilling. As stated in its name, CBHP MPD maintains constant pressure at a certain depth of wellbore for a mud weight. The mud pump rate can be changed to maintain a constant wellbore pressure at any operating condition, whether it is static or dynamic [45].

CBHP MPD uses the procedure of adjusting the mudflow rate and surface backpressure to circulate a small to medium-sized kick out of the well safely and efficiently without shutting the well [95]. Table 3 listed some essential features in terms of kick handling of conventional and CBHP MPD methods. A comparison shows that the CBHP

Table 2 MPD variants with their objectives

MPD variants	Constant bottomhole pressure (CBHP)	Dual gradient drilling (DGD)	Pressurized mud cap drilling (PMCD)
Unknown drilling window	√	X	X
Slow ROP	√	X	X
Severe loss of circulation	X	X	√
Sour formation	X	X	√
Avoid gross overbalance	X	√	X
Ballooning problem	√	X	X
Well control risk	√	X	X

√ yes, X no

Table 3 Key differences between conventional drilling versus CBHP MPD

Key features	Conventional drilling	CBHP MPD
Surface backpressure applied	X	√
Maintain a constant bottomhole pressure	X	√
Prompt kick identification	X	√
Find unwanted flux in the system	X	√
Support alternative method of well control	X	√

√ yes X no

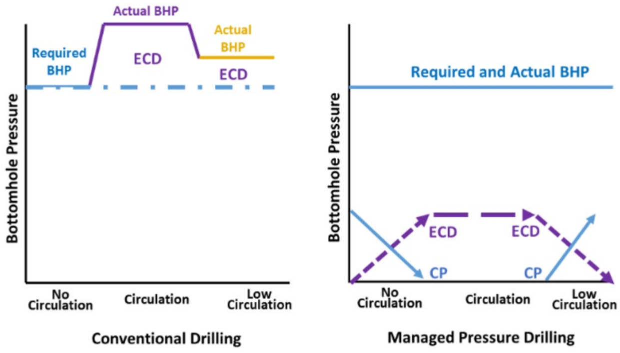


Fig. 2 Bottomhole pressure response versus drilling methods. Redrawn from Saponja et al. [163]

MPD method outperforms the traditional methods in terms of well control, pressure, and influx management during the drilling operation. Therefore, this study focused on CBHP MPD operation.

Dynamic well control has a physical limit of the equipment in handling a gas kick due to the surface facility limitations, equipment integrity and safety concerns. A small gas influx in the bottomhole can be as high as 100 times of original volume at the surface. Influx size is a vital issue in offshore drilling, where kick fluid volume of fewer than ten barrels is desirable for the safe circulation of a kick [95]. Thus, there is a volumetric limit for all MPD setups that can handle a gas kick. For this reason, early detection of a gas kick is crucial for the safe operation of managed pressure drilling and well control. An early kick detection ensures the minimum kick size in the wellbore during kick circulation.

2.3 MPD versus well control tools

In conventional drilling, the required and actual bottomhole pressure varies based on the well circulation status. In contrast, both actual and required bottomhole pressure remains the same in MPD irrespective of well circulation, as shown in Fig. 2.

MPD prevents continuous circulation of influx to the surface. The goal is to maintain a constant bottomhole pressure and circulate kick with a suitable method such as Driller's methods. Ensuring the wellbore and equipment integrity during circulation prevents any flow from the formation [198]. When there is no flow, or at low the pump rate, the bottomhole pressure also tends to reduce, due to loss of the annular frictional pressure drop ($\Delta P_{Friction}$). In the MPD system, this reduction in the frictional pressure drop component can be compensated by applying additional backpressure. It also adjusts the casing pressure to maintain a constant bottomhole pressure. When a mud pump's circulation restarts, the induced additional backpressure is reduced to increase the equivalent circulating density (ECD) of the system [70, 132, 133]. Though MPD can partially serve dynamic well control by manipulating parameters like surface backpressure, mud density and pump rate, however MPD is not an absolute well control method. By manipulating the choke, it is possible to control the influx from the well without shutting the well. However, MPD can handle a limited volume of kick and kick intensity that needs to be estimated in advanced.

2.4 Managed pressure drilling operating principle

Figure 3 shows a typical arrangement of a typical MPD setup of CBHP. The strategic equipment of this control mechanism is a Rotating Control Device (RCD). The role of RCD is to control and divert upstream flow through choke manifold. It also maintains the annular isolation of the drill string and the well. The setup has the provision for working as MPD as well as conventional drilling since the outlet from the RCD can be diverted to the main flowline or MPD choke manifold.

MPD choke manifold is another critical component that enables variable flow restriction to maintain a constant bottomhole pressure at any operating condition. The primary purpose of the choke manifold is to control the well pressure, not the flow rate. Once an influx is detected, the choke is automatically adjusted to increase the surface backpressure to control the influx. Finally, it can be circulated out by mud gas separator through MPD manifold.

3 Reservoir kick

A kick initiates an uncontrolled flow of formation fluid towards the wellbore that dominates the well control to a state of emergency during a drilling operation. The kick may occur if a well is drilled in a hydrocarbon-bearing formation that has a higher pressure than the pressure of the wellbore, thus prompting the formation influx to flow towards the wellbore. Various types of formation fluids such as gases, hydrocarbons, oil, water, or any combination of different fluids can enter the wellbore during a kick. Among different formation fluid, a gas kick is more severe due to a dramatic expansion of the gas when it reaches the surface. A 10 years' statistics [200] showed that approximately 6% kicks occurred in exploratory wells, whereas this figure is around 3.2% for development wells. For both categories, a kick is most likely to occur at a depth higher than 4000 m. Holand and Awan [82] showed a statistical analysis of 576 wells from the Norwegian Continental Shelf, with 9% kick in standard drilling, 32% kick in deep-water drilling and 139% kick at HPHT well, as shown in Fig. 4.

3.1 Reason for kick

There are several reasons for the occurrence of a kick. The most important reason is the low wellbore pressure. Low wellbore pressure can occur in two ways:

1. *Drilling mud weight is low compared to the anticipated weight* A sudden mud density drop causes lower pressure in the wellbore, or the formation pressure becomes higher than anticipated. Thus, the hydro-

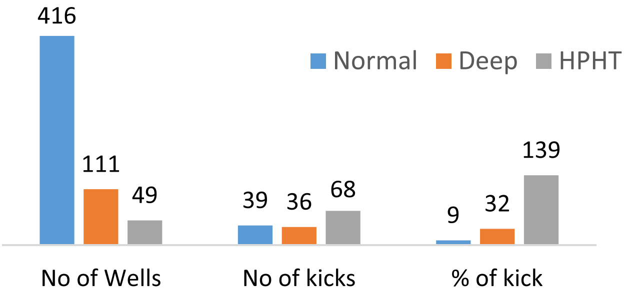


Fig. 4 Kick statistics for normal drilling, deep water drilling and HPHT drilling [82]

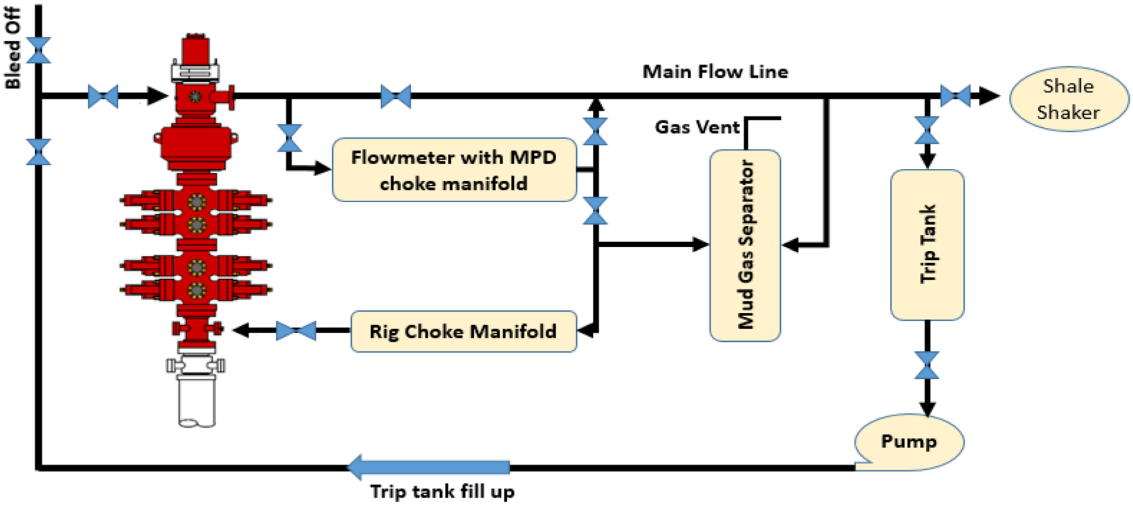


Fig. 3 MPD setup of a closed wellbore system. Adopted from Nas [131]

static pressure applied by the mud weight is insufficient to counterbalance the formation pressure at the wellbore.

2. *Dynamic and transient wellbore pressure condition* The relative movement of the drill pipe during tripping in the wellbore causes a transient environment, which may also reduce the wellbore pressure compared to the pore pressure.

Apart from low wellbore pressure, formation and fluid characteristics are also closely related to kick. There are three primary conditions for a kick to occur [131]. They are:

1. *Pressure inequality* Exposed formation pressure is higher than the wellbore pressure.
2. *Permeability* The reservoir section of interest has a substantial permeability so that it can allow the influx fluid to flow into the wellbore; and
3. *Viscosity* The formation fluid has a low viscosity that enables a smooth flow into the wellbore.

Gas kick might also occur if the operator loses well control during a drilling operation, even in the case of managed pressure drilling [205]. Table 4 shows the major reasons for loss of primary well control and the corresponding change in environmental variables that lead to a kick.

Insufficient mud weight and inadequate borehole-filling have high impacts on loss of well control and hydrostatic imbalance. Lost circulation has a moderate effect, and swabbing has minimal effect on the loss of well control. Moreover, a kick may occur due to some other causes e.g. sudden mud pump failure, decreasing ECD, and loss of control in backpressure during MPD operation. Figure 5 shows a statistical analysis of 85 kicks in deep-water drilling. Insufficient mud weight or low borehole filling causes almost 50% of kicks. Swabbing and gas cut mud is responsible for another 30% of total kicks.

3.2 Kick warning signs

In a regular drilling operation, mudflow into the wellbore must be equal to the mudflow out of the wellbore. Any kick in the bottomhole violates this steady-state balance of drilling mud circulation. When a kick initiated at the bottomhole, the influx towards the wellbore causes an increase in the outlet mud flow rate at the surface. Researchers defined different kick detection methods ranging from simple [40, 89, 181] to several complex methods [38, 69, 76, 78].

A kick initiates with one or more direct or indirect warning signs. Different kick warning signs, along with their importance to kick identifications, are tabulated in Table 5. All warning signs are grouped into two categories based

Table 4 Reason for loss of well control leading to a gas kick

Reason of loss of well control	Drilling environment parameter									Consequence
	High annular frictional loss	High pulling speed	Excessive pipe running speed	High MW	Drilling in natural fissures and fractures	Larger OD drilling tools and hole geometry	Sudden penetration of high permeable formation	Improper tripping operation	Low mud density	
Insufficient mud weight	×	×	×	×	×	×	√	×	√	Underbalanced situation
Insufficient filling of the borehole	×	×	×	×	×	×	×	√	×	Hydrostatic imbalance
Lost circulation	√	×	√	√	√	×	×	×	×	Total or partial mud loss
Swabbing	×	√	×	×	×	√	×	×	×	Reduce hydrostatic pressure
Abnormal Pressure Formation	×	×	×	×	×	×	√	×	×	Sudden kick

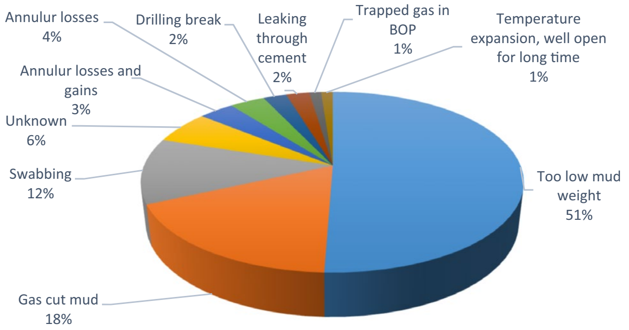


Fig. 5 Comparative study of reasons for gas kick. Data obtained from Holand and Awan [82]

on their significance level. Signs such as flow rate, increase in pit volume, flowing well with mud pump off, and inadequate borehole-filling during a trip are direct indications of an upcoming kick. These indications are termed as primary kick indicators with high significance. A high significance warning sign requires quick attention from the rig's personnel. A change in drill string weight, cut mud weight, sudden drilling break, and change in mud pump pressure are the indirect measurements of kick. These indirect measures are known as secondary kick warnings. The significance of secondary kick warning in kick indication is quite less.

3.3 Flow measurement for kick identification

The oil industry widely uses flow measurement as a primary kick identification tool. Most industrial flow measurement devices can measure the velocity, volumetric flow rate and mass flow rate of gas, liquid or any vapour flowing through the tubing/piping. In managed pressure drilling, a mass flowmeter, especially the "Coriolis Flowmeter," is widely used to detect the return flow rate. A continuous flow in Coriolis flowmeter is required to identify a kick. For any intermediate operation like tripping, making a connection or any interruption of fluid circulation, the Coriolis meter does not work effectively. For a mass flowmeter, Kinik [100] proposed flux calculation as

$$Q_{in} = \int_{t1}^{t2} q_{in} dt \tag{2}$$

where q_{in} is defined as the mass flow meter reading at the inlet of the system and Q_{in} is the total flux during the time interval t_1 to t_2. Similarly, for outflow, [100]

$$Q_{out} = \int_{t1}^{t2} q_{out} dt \tag{3}$$

Then the difference in flux is calculated by employing Eqs. (2) and (3) as:

$$\Delta Q = Q_{in} - Q_{out} \tag{4}$$

The time interval is defined as $\Delta t = t_1 - t_2$; usually, this time interval is 1–10 min, based on different drilling parameters and operating conditions. Jiang et al. [92] proposed a trigger value for a kick and fluid loss at $Q_k = Q_L = 80L$ for the very deep well. So, it is assumed that a kick had occurred when $\Delta Q \geq Q_L$ and loss took place when $\Delta Q \leq -Q_K$. Fredericks et al. [59] proposed a kick detection method based on accurate return flow measurements and simultaneously measured the wellbore pressure with a special downhole arrangement.

3.3.1 Flow measurement as early kick detection tools and kick response time

Continuous and accurate measurement of the mass flow rate and density of the working fluid ensures drilling efficiency, predicts influx movement, and reduces the nonproductive time (NPT). A mass flowmeter can quickly detect a kick and early detection can significantly reduce kick size during detection time. Fraser et al. [58] proposed three key performance indicators for analyzing a kick.

Table 5 Standard kick indicators and their significances

Kick warning sign	Attributes	Indicator level	Significance level
Flow rate increases	$Q_{out} > Q_{in}(Constant)$	Primary	High
Pit volume increases	$Q_{out} > Q_{in}$	Primary	High
Flowing well with mud pump off	$Q_{out} = +ve, Q_{pump} = 0$	Primary	High
Downhole pressure measurement (PWD)	*Sudden downhole pressue change*	Primary	High
Drilling break	*Change of ROP*	Secondary	Medium
Cut mud weight	$MW_{surface} \downarrow$	Secondary	Low
Change in pump pressure	$P_{pump} \downarrow$	Secondary	Low
Change in drill string weight	$W_{drill\_string} \downarrow$	Secondary	Low

These are: (1) Kick detection volume, (2) Kick response time, and (3) Drilling mode kick frequency. A comparison of early kick detection volume for conventional methods with and without an outflow meter, as shown in Table 6.

The drilling mode kick frequency expresses the relative frequency of kick occurrence based on different drilling operations. Fraser et al. [58] showed that 70% of kicks are likely to happen while making a connection to the drill pipe. Approximately 15% of kicks occurred during the tripping operation, while all other reasons account for another 15% of kick frequency. The use of a flowmeter can significantly reduce the influx volume by 50–70%. A flowmeter plays a vital role in detecting a kick at the earliest possible time with a minor change in outflow volume. Concerning well control strategy, with a reduced influx volume, kick response time is also significantly lowered.

Fraser et al. [58] proposed three key performance indicators, but their study did not establish any correlation between kick detection volume and response time. However, kick detection volume and kick response time mostly depend on operational practice, geological nature, well trajectory, the technology used and crew skills etc. Kick response time is the sum of the time for gradual reduction of flow rate in the mud pump, a return flow check, closure of the blowout preventer (BOP) and all other related operational delays. Kinik et al. [101] investigated the consequence of total response time on all drilling variables during well control. They [101] showed that response time is the only variable that can be managed and concluded that kick size mostly depends on the total response time. Their simulation showed that the response time can be up to 10 min for conventional drilling with a 50 bbls kick. Response time is much shorter in case of a closed-loop MPD. It is only 4 min with 1.88 bbls kick. Their study revealed that MPD allows faster response to a kick with low influx volume.

3.3.2 Coriolis flowmeter application in MPD and its limitations

In an MPD system, a Coriolis flowmeter is widely used because of its high accuracy. A Coriolis flowmeter is independent of fluid properties like viscosity and density. However, the Coriolis flowmeter is expensive and has limitations regarding operating pressure, temperature and types of fluid handled. Based on the design, it can work in an environment where the temperature is as high as 350 °C and pressure is 5000 psi [194]. During operation, it invariably requires 3–5 psi pressure drops which indicates that it needs to be set up in a closed wellbore system like MPD. Another drawback is that a Coriolis meter does not provide an accurate result until the flow line is fully loaded or when the return mud contains gas. These limitations of the flowmeter show the need for further research and improvement of the kick detection system in MPD.

3.4 Acoustic measurement of gas kick

Acoustic behaviour of gas along the wellbore gives valuable information about kick propagation in the well. Bryant et al. [32] demonstrated a method of gas influx detection by observing the acoustic response of MWD tools. However, the performance of acoustic kick detection largely depends on some specific factors such as circulation rate, drilling fluid types and the tool's response frequency etc. A recent study [62] demonstrated that the drilling mud density and mud injection rate have an enormous influence on acoustic kick measurement. Different researchers described different gas kick detection methods using acoustic behaviour in the wellbore. Table 7 shows various gas kick detection methods based on acoustic measurements. Sonic methods easily detect an early gas kick; however, most of the sonic kick detection methods are based on water-based mud only. Due to significant limitations with oil-based mud, the drilling industry cannot solely rely on the acoustic measurement of a gas kick.

3.5 Kick identification by log interpretation

Mud logging analysis always shows precise information such as formation type, return fluid density and types of return gas. Analyzing the return fluid and cuttings gives valuable information about the formation. Al-Morakhi et al. [8] investigated micro-mud log analysis for real-time

Table 6 Early kick detection frequency versus different drilling operations

Estimated drilling mode kick frequency (%)		Tripping out	Making a connection	Drilling ahead	Out-of-the-hole	Plug and abandon
		15%	70%	5%	< 5%	< 5%
Conventional drilling without a flowmeter	Estimated kick detection volume	~ 3 bbl	> 10 bbl	> 10 bbl	~ 5 bbl	> 10 bbl
Conventional drilling with a flowmeter		~ 1 bbl	~ 5 bbl	~ 3 bbl	~ 5 bbl	~ 5 bbl

Table 7 Different acoustic kick detection methods and their limitations

Researcher	Bryant et al. [32], Bryant and Wallace [33]	Codazzi et al. [41]	Stokka et al. [175]	Bang et al. [23]	Li et al. [105]	Tseytlin [190]
Can detect early gas kick	X	√	√	√	√	√
Identify free gas	√	√	√	√	X	X
Independent of influx location	Y	X	√	√	√	√
Applicable for oil-based mud	X	X	X	X	X	X
Can detect dissolved gas	X	X	X	X	X	X
Determine presence of gas annulus	X	X	√	X	√	√
Identify connection gas and trip gas	√	X	X	√	X	X
Identify influx size	X	X	X	X	X	Y

√ yes, X no

drilling and early kick detection. The micro-mud sensor can work on both oil-based mud and water-based mud, and simultaneously monitor different drilling parameters every 5 s while monitoring the drilling progress. For the reservoir with a fracture, this log analysis can be used as a tool for early kick detection. However, for a high percentage of gas return, the micro-mud sensor produces a significant error.

Ahmed et al. [5] proposed diversification of the conventional kick detection method using real-time mud logging data for early kick detection. Monitoring the real-time mud logging data provides seven parameters for kick detection: pit gain at the surface, mudflow rate, drilling rate of penetration, total gas, pump off gas, connection gas and any drop in the pump pressure. Their proposed method can detect a small kick as well as predict any near-balance state of kick, which is going to occur. However, it is not an entirely reliable kick detection method. Additional apparatus such as an accurate flow check and trip tank must be integrated with the mud log data to understand the kick nature fully.

3.6 Kick identification by statistical method

The statistical method uses historical information from the nearby well, field, and geological information to predict the possibility of potential kick from a well or formation. Hargreaves et al. [76] proposed a kick detection method based on a Bayesian statistical method where an animated decision was generated based on regular noisy field data. This method shows improvement in deep-water drilling and the heaving condition. However, all statistical methods depend heavily on the accuracy of raw data. Raw data can vary with the geological location. So, a statistical method of kick identification can be used as a supporting tool for a forthcoming kick in any known formation. The major drawback of the statistical method is that it cannot be utilized for any unknown formation with confidence. Dedenuola et al. [46] investigated historical kick volume under normal distribution to estimate the kick tolerance by a statistical model. They modelled historical data for kick volume against zero kick intensity and kick intensity against zero kick volume. This estimation also depends on formation geology, well location, well-depth, and fluid rheology.

4 Modelling, simulation and control of MPD system

A kick often creates a multiphase flow environment in the wellbore and annulus. For example, a gas kick always makes a two-phase flow in the annulus. The phenomena of gas bubble rise in the wellbore need to be understood first to investigate the nature of a gas kick. Below, different studies related to understanding gas kick, modelling and control are summarized.

4.1 Factors affecting the gas bubble rise velocity in the tubing

Most of the two-phase flow models are based on small-scale experimental results for vertical wells, inclined tubing, and annuli. These simple models do not represent actual complex wellbore geometry in real-time drilling operations [180]. Different mechanistic models characterize the annular behaviour of two-phase flow which were proposed by different researchers [35, 43, 54, 96, 103, 108, 142, 180]. Rader et al. [148] proposed several factors that affect gas bubble rise velocity in a pipe and annulus. They identified the factors as the phase densities and viscosities of gas and liquid, fluid velocity, gas expansion rate and geometric orientation of the pipe show effect to the gas bubble rise velocity. Santos and Bourgoyne [161] proposed a two-phase flow regime with a pressure profile approximation along the wellbore. Skalle et al. [168] investigated the upward gas migration velocity in the annulus. Asakereh [17] investigated a flow regime analysis based on an annular acceleration parameter to detect shallow gas kick.

Table 8 summarizes several factors that affect the rise velocity of gas bubbles in the wellbore and their relative impact on bubble propagation along the annulus. Annular geometry has the highest impact on bubble propagation along a wellbore. Liquid velocity and gas expansion rates have considerable influence. In the case of mud viscosity and wellbore orientation, the effect is minimal. Apart from these four parameters, other factors have a negligible effect, as listed in Table 8.

4.2 Mathematical model of gas kick

An appropriate mathematical model can properly describe a kick circulation within the wellbore. Several researchers proposed different mathematical models to quantify the behaviour of gas kick in the wellbore. The following two approaches are used to simulate a gas kick: (1) *Mathematical modelling,* in association with the material balance equation and (2) *Hands-on methodology,* in-field test facilities, to study the kick behaviour under a real wellbore condition [94].

LeBlanc and Lewis [104] proposed a basic mathematical model in a controlled gas kick that used to approximate annular backpressure, equivalent mud densities and gas kick effect on casing pressure. However, gas specific gravity, influx size and gas cut drilling mud also have a detrimental effect on the casing pressure and equivalent circulating density. Mathews and McKenzie [116, 118] proposed different gas kick models based on pseudo-steady-state behaviour. Nickens [135] proposed a vertical well model that accounts for gas influx as a function of the formation properties and the wellbore bottom hole's operating condition. Hovland and Rommetveit [84] investigated the consequence of various constraints on gas migration velocity using a full-scale experimental setup. Many studies, both experimental and modelling [1, 56, 79, 102, 108, 147, 182, 183, 196] focused on gas kick migration and transient behaviour, flow analysis, characteristic parameters, density distribution and annular pressure loss.

Table 9 summarizes several mathematical models for the gas kick with their applicability and limitations. Most of the gas kick models are transient models with a vertical well assumption. Very few studies [79, 147, 192, 196] described gas kick models for horizontal and deviated wells. Few models are validated through gas kick experiments in the laboratory [79, 102, 104, 147, 192]. Table 9 shows that most of the existing models are not capable of detecting influx. Almost all mathematical models ignored the lost circulation effect. Gas solubility in oil-based mud makes it difficult to estimate the behaviour of the gas kick along the wellbore. Few studies [147, 192] included gas solubility in the oil-based mud while propagating a transient gas kick in the wellbore. Till now, no comprehensive model is available for a gas kick to describe the complex wellbore and annulus flow behaviour.

4.3 Control system design for kick identification

An automated control system is a key to a successful operation in managed pressure drilling. In the MPD system, typical control variables are the flow rate of the drilling fluid, drilling fluid density, surface backpressure and downhole pressure at a specific depth. The control system always measures the return flow and compare it with an ideal condition, which enables it to find any discrepancies in a very brief period.

4.3.1 Control objective

In an automated MPD controller, the main objective is to monitor the pressure profile along the wellbore and maintain the desired flow rate corresponding to the system pressure. The controller also performs several

Table 8 Factors affect bubble rise velocity in wellbore

Factors	Dependency on other parameters	Impact on bubble rise velocity
Fluid density	Independent	Negligible
Gas void fraction	Independent	Negligible
Mud rheology	Independent	Negligible
Mud viscosity	Decreases with increasing annulus size	Small
Surface tension	Independent	Negligible
Pipe inclination	Maximum rise velocity as 45°	Small
Gas expansion rate	Depends on annulus backpressure	Significant
Annular geometry	Increase with increasing annular diameter	High
Liquid velocity	Increasing with flow velocity	Significant

Table 9 Different mathematical models of a gas kick

Researcher	Model	Model type	Well type	Lateral Consideration	Two-phase model	Temperature Gradient	Concentric Model	Consider Loss circulation	Influx Type Identification	Kick Migration	Field/Experimental Investigation	Mass Transfer	Oil Based Mud	Sour formation	Limitation
LeBlanc and Lewis [104]	$P_{1-2} = P_{csi} + \left[\frac{V_i - V_1}{C_A}\right]\left[\left(\frac{dp}{dx}\right)_{ODM}\right]$ $V_c \leq V_{dp}$	Static	vertical	X	√	√	√	X	X	√	√	X	X	X	Ignored the effect of variable annular volume
Maus et al. [117]	$\Delta V = \int_0^t Atdt\ ; \Delta P = -B\Delta V$	Transient	vertical	X	√	X	√	X	√	√	X	X	X	X	Model performance largely depends on instrument sensitivity
Hoberock and Stanbery [81]	$\frac{1}{\rho}\frac{\partial \hat{P}(z,t)}{\partial z} + \frac{\partial \hat{U}(z,t)}{\partial t} + \int_0^t \phi(u).\frac{\delta \hat{U}(z,t-u)}{\partial t}du = 0$ $\frac{1}{C^2}\frac{\partial \hat{P}(z,t)}{\partial z} + \rho\frac{\partial \hat{U}(z,t)}{\partial z}=0$	Transient	vertical	X	√	√	√	X	X	X	X	X	X	X	Heat transfer effect in dynamic model was ignored
Nickens [135]	$\frac{\partial}{\partial t}\left[\rho_m v_m(1-\lambda) + \rho_g v_g \lambda\right]$ $+\frac{\partial}{\partial z}\left[\rho_m v_m^2(1-\lambda) + \rho_g v_g^2 \lambda\right] + \frac{\partial p}{\partial z}$ $+\left(\frac{\partial p}{\partial z}\right)_f + \left[\rho_m(1-\lambda) + \rho_g \lambda\right]g = 0$	Transient	vertical	X	√	√	√	X	√	√	X	X	X	X	Limited to a single kick in a vertical well with drill bit location at bottom only
Lage et al. [102]	$P_s = \frac{1}{X_m} ln \frac{V_m - V_{go}}{V_w + V_f - \frac{P_{go}V_{go}}{P_s}}$	Static	vertical	X	√	X	√	X	X	√	√	X	X	X	The model cannot be applied to the transient wellbore condition.

Table 9 (continued)

Researcher	Model	Model type	Well type	Lateral Consideration	Two-phase model	Temperature Gradient	Concentric Model	Consider Loss circulation	Influx Type Identification	Kick Migration	Field/Experimental Investigation	Mass Transfer	Oil Based Mud	Sour formation	Limitation
Wang et al. [196]	$\frac{\partial}{\partial t}\left[A(1-\lambda)\rho_l\right]+\frac{\partial}{\partial z}\left[A(1-\lambda)\rho_l v_l\right]=0$ $\frac{\partial}{\partial t}\left[A\lambda\rho_g\right]+\frac{\partial}{\partial z}\left[A\lambda\rho_g v_g\right]=0$ $\frac{\partial p}{\partial z}+\left(\frac{\partial p}{\partial z}\right)_f+\left[\rho_l(1-\lambda)+\rho_g\lambda\right]g cos\theta=0$ $V_g=C_o\left[(1-\lambda)v_l+\lambda v_g\right]+v_s$	Transient	Horizontal	√	√	Constant	√	√	√	X	X	X	X	X	Gas rise velocity in the whole range of deviation from horizontal to vertical section is not modelled
Vefring et al. [192]	$\frac{\partial}{\partial t}\left[A(1-\alpha)\rho_l v_l+A\alpha\rho_g v_g\right]=-\frac{\partial}{\partial s}(Ap)$ $-Af_1-Af_2+A\left((1-\alpha)\rho_l+\alpha\rho_g\right)g cos\theta$ $-\frac{\delta}{\delta s}(A(1-\alpha)\rho_l v_l^2+A\alpha\rho_g v_g^2$	Transient	Deviated and Horizontal	√	Single- and two-phase flow	Constant	√	X	X	√	√	X	√	X	Laboratory scale experiment does not show any significance for gas dissolution and mass transfer rate
R. Rommetveit [147]	$v_G=\sum_{i=1}^{N}C_i x_i$ $\frac{dp}{dx}=\sum_{i=1}^{N}C_i y_i$ Laminar flow representation $2R_{ecc}x_{lam,G}f_{lam,G}\rho_G v_{S,G}^2/D_{eff}$ $2R_{ecc}x_{lam,L}f_{lam,L}\rho_L v_{S,L}^2/D_{eff}$ Turbulent flow representation $2R_{ecc}\left(1-x_{lam,ns}\right)f_{turb,ns}\rho_{ns}U_{mix}^2/D_{eff}$ $Ci=coefficient$	Transient	Horizontal	X	√	X	X	X	X	√	√	X	√	X	Vertical and inclined well model are not valid for horizontal well for gas transportation

Table 9 (continued)

Researcher	Model	Model type	Well type	Lateral Consideration	Two-phase model	Temperature Gradient	Concentric Model	Consider Loss circulation	Influx Type Identification	Kick Migration	Field/ Experimental Investigation	Mass Transfer	Oil Based Mud	Sour formation	Limitation
He et al. [79]	The slip velocity of the bubble flow $v_b = 1.53\left[\frac{\rho g(\rho_l-\rho_g)}{\rho_l^2}\right]^{0.25}(1-\alpha_g)^n sin\theta$ Slip velocity of the slug or churn flow $v_{tb} = (0.35sin\theta + 0.54cos\theta)\left[\frac{gD_{ep}(\rho_l-\rho_g)}{\rho_l}\right]^{0.5}$	Transient	Vertical	X	√	Linear	√	X	X	X	√	√	X	√	Radial flow of the drilling fluid in the wellbore ignored
Aarsnes et al. [1]	$\frac{\partial v_G}{\delta t}\left(h_G\rho_L + \frac{M_G}{A}\right) = p_G - p_c - \rho_L g h_G$ $-fv_G^2\left(h_G\rho_L + \frac{M_G}{A}\right)$	Transient	Vertical with riser	X	X	Linear	X	X	X	X	X	X	X	X	Field scale test was not fully successful due to rapid gas bubble expansion in the riser
Fjelde et al. [57]	Gas density model: $\rho_g = \frac{P}{a_g^2}$ Liquid density model: $\rho_l = \rho_{l,o} + \frac{(P-P_0)}{a_l^2}$ Gas slip model: $v_g = Kv_{mix} + S = K(v_l\alpha_l + v_g\alpha_g) + S$ Friction gradient model: $F_w = \frac{2f\rho_{mix}v_{mix}abs(v_{mix})}{(d_o-d_i)}$	Transient	Vertical	X	√	Isothermal	X	X	X	X	X	√	X	X	Non-Newtonian fluid does not show the unique result of kick migration and gas rise velocity in the wellbore Mud rheology for non-Newtonian fluid needs to be reviewed carefully.

operational and failure indicators [151] for the drilling system like kick detection and lost circulation etc.

4.3.2 Controllers in drilling automation

With technological advancements, the drilling industry is rapidly shifting from manual drilling to automated drilling and well control systems. For an automated control system, potential controller algorithms vary based on their application, ranging from a simple proportional integral derivative (PID) controller to advanced nonlinear model predictive controllers (NMPC). The precise control of a drilling system and its response largely depend on the control system design. In the drilling application, many researchers [66, 77, 128, 153, 166, 213] proposed feedback controllers that can track system status like choke pressure and bottomhole pressure etc. from several physical locations of the drilling system.

A predictive controller is used to control the flow rate and choke opening based on the fluctuating flow of the return line. The NMPC controller shows better performance in field applications than the PI controller since a PI controller needs to be changed based on the operating condition. Several authors proposed a wide range of predictive controllers in the MPD applications. A multivariable controller showed a promising result in rejecting the disturbances and regulating BHP [31]. Eaton et al. [49] proposed three model predictive controllers with advanced switching algorithms in MPD operations. Nandan [127] proposed a robust NMPC controller that can automatically switch from pressure control mode to flow control mode in case of a gas kick while drilling.

4.3.3 Non-linear model predictive controller design principle

Lab-scale NMPC controllers were designed by several researchers to achieve target objectives like a pressure control and flow control in the MPD system. Mudflow rate and choke opening are the primary sources of pressure manipulation by an NMPC controller. Choke opening is controlled by the required back pressure to maintain the desired bottomhole pressure.

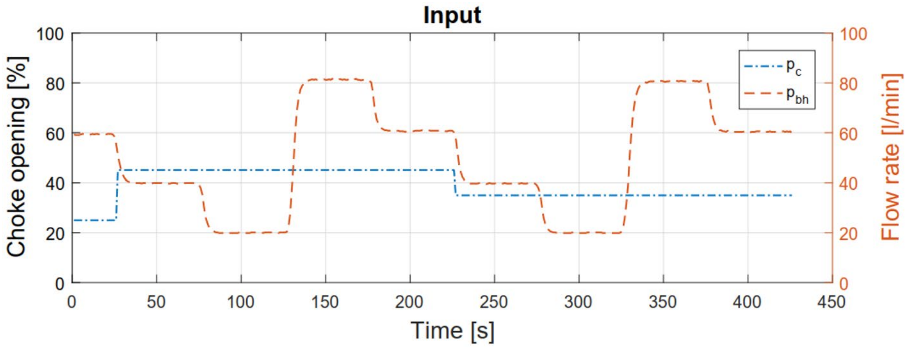
The NMPC utilized a nonlinear Hammerstein Weinner (H-W) model for prediction and a genetic algorithm for calculating optimal control input. Figure 6 shows a typical Hammerstein model. At the input function, with a variation of bottomhole pressure, the casing pressure is adjusted accordingly, as shown in Fig. 7. Figure 8 shows the output of the NMPC for measured pressure and NMPC simulated pressure.

4.3.4 Kalman filter

The reservoir management system widely used Kalman filter for many years; however, in recent days, it is also used in the drilling automation [68, 69, 90, 91, 111]. In designing a managed pressure drilling automation system, an appropriate design of the control system is very much essential to detect any fault during the drilling operation. A drilling fault can cause a change or deviate in the flow rate or pressure in the system from the expected value. The basic principle behind the control system is to use known input and output values to calculate or estimate the unmeasured data like system pressure, return flow rate or ever more uncertain data like dynamic frictional pressure drop in the annulus section during normal state or operation of a

Fig. 6 Hammerstein Weiner model (Matlab 2018b)

Fig. 7 NMPC input parameter [15]



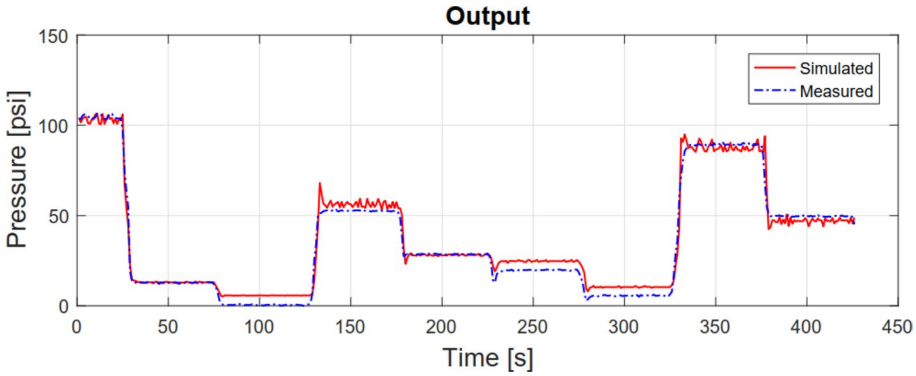


Fig. 8 NMPC output response [15]

kick in the system. An unscented Kalman filter (UKF) based ensemble classifier can detect a fault in drilling operations like lost circulation or gas kick. A detailed analysis of fault nature can give an estimation of the current state of deviated behaviour in real-time.

4.3.5 Adaptive and PID control system

Proportional integral derivative (PID) used as an automatic feedback controller due to ease of use and implementation in the drilling system. A PID controller is widely used where there is no variation in parameters in the system since it requires proper tuning from time to time. However, during a real-time drilling operation, the system properties like drill string velocity, rotation, fluid velocity, density, rheology changes with time, which all influence the bottom hole pressure. To adapt varying changes during the drilling operation, the PID controller should be adjusted accordingly. Drilling engineer utilizes the PID controller to control the downstream choke and stabilize the downhole pressure in the system. Researchers [71, 123, 166, 172, 211, 212] proposed different approach of PID controller in drilling operation to maintain the flow rate and bottom hole pressure for kick mitigation.

4.3.6 Control system application in MPD kick identification

Santos et al. [160] first introduced the concept of 'Micro-Flux Control' for a closed well based on fluid loss or influx detection. It instantly takes corrective measures to adjust the return flow rate and keeps the bottomhole pressure constant to regain well control. Several other studies [37, 39, 48, 63, 72, 73, 119, 146, 152, 154, 163, 191, 193] proposed different control systems for MPD kick detections, equipment failure, influx management, and wellbore pressure maintenance.

Kinik et al. [100] demonstrated an automatic early kick detection method and a control mechanism to minimize kick influx by eliminating the requirement for flow check and reducing the operational delays. Bacon et al. [20] demonstrated the advantage of the dynamic influx control techniques of MPD over the conventional drilling method. Dynamic influx control shows extensive benefits regarding well control, reduced influx size, and flexibility in kick circulation, compare to traditional methods. MPD dynamic influx control method leads to increased safety and efficiency in the overall drilling operation.

5 Response to kick in MPD

In conventional drilling, the initial response to a kick is well defined with standard procedures like Driller's methods, Wait and Weight method or the Bull-heading method. Kick circulation methods are selected based upon specific well condition. Gas migration location, circulation rate, mud properties, fracture gradient, and maximum allowable annular surface pressure are some of the critical factors that influence the kick circulation method. The primary well control for constant bottomhole pressure MPD is an upgrade of the Driller's method for conventional well control. The control equipment used in MPD facilities supports alternatives to the typical shutting off the well with BOP.

5.1 Alternative response to kick in MPD

In the drilling industry, preliminary response during a kick must be explicitly specified before recognizing a kick while drilling, so that the rig personnel can work quickly and appropriately. Response to a gas kick is very much dependent on well geometry, the relative position of a kick zone and any weak regions in the wellbore. IADC has specified a regulation and guideline for responses that should be taken for an indicated formation flow. Minerals Managements Service (MMS) has defined a well control matrix for the possible response. However, no response provides a conclusive basis for the action to be taken for a particular case like CBHP MPD [170].

Responses to a kick taken in managed pressure drilling can be grouped into two categories: circulating response and non-circulating response as shown in Table 10. A non-circulating response is also known as a direct shut-in or static method. The broadly acceptable non-circulating response is to shut the mud pump and close the choke in the quickest possible time. Another variation of non-circulating response is to "schedule mud pump shut down," followed by a return flow check at the surface. The latter method offers a chance to check whether the casing pressure is sufficient to stop the formation flow, or if it needs to completely shut down the well with a higher casing pressure, indicating that the kick has been taken.

Table 11 summarizes four common initial responses to kick during MPD. Once a kick is detected, an immediate shut-in of the well is the most appropriate response since this does not require any other special equipment. The modified MPD pump shutdown procedure with a choke flow check is beneficial when an uncertain kick likely to happen or a slow kick is observed. Increasing the casing pressure eliminates any pressure variations, maintains the ECD and hence is a preferred method for kick response. Increasing the pump rate provides minimum casing shoe pressure and a large safety window to avoid lost return at the previous casing shoe. However, for a typical kick scenario, no single response considered as the best response. All methods are preliminary, and a single response does not apply to all situations to kick during MPD.

Table 10 Circulating response versus non-circulating response to a kick

Response type	Circulating response	Non-circulating response
Need flowmeter	Yes	No
Need special equipment	Yes	No
Can be applied when surface equipment fails	No	Yes
Pressure at casing shoe	Low	High
Risk of lost return for weak zone above kick zone	Low	High
Response time	Short	Delayed
Kick size	Smaller	Larger
Pressure fluctuation at bottomhole	Low	High
Choke pressure and casing shoe pressure variation	Low	High
Pit gain at surface	Low	High
Response varies with well geometry	Yes	No

Table 11 Comparison of initial response to a kick in MPD

Response	Shut in	Modified MPD pump shutdown	Rapid increasing the casing pressure	Stepwise increasing the pump rate
Response type	Non circulating	Non circulating	Circulating	Circulating
Flow check	X	√	√	√
Check for low rate kick	X	√	X	X
Need for special equipment	X	X	√	√
Minimum risk of lost circulation	√	X	√	√
Well defined procedure	√	X	X	X
Minimize casing shoe pressure	X	X	X	√
Applicable for large hole size	√	√	√	X
Requires accurate flow metering	X	X	√	√
Executed by surface BOP	√	X	X	X
Detect lost return	X	X	√	X
Wide safety margin	X	X	√	√
Quick kick detection	X	X	√	X
Maintain underbalanced condition	X	√	X	X
Pressure fluctuation at bottomhole	√	X	X	X

√ yes, X no

5.1.1 Kick response to compressible flow

For general kick response, the preliminary assumption is based on a "flow continuity". It indicates that there is no influx for incompressible fluid flow. Flow continuity is not truly applicable to any compressible fluid flow in the wellbore. For a compressible flow, obtaining $Q_{out} = Q_{in}$ does not prove an influx stops. Bacon et al. [22] investigated the transient kick response to multiphase compressible flow behaviour in the wellbore with a control volume approach. They proposed a dynamic response by applying a backpressure method to obtain the $Q_{out} = Q_{in}$ and maintain this condition until the influx stops. During a gas kick, influx cessation may occur when $Q_{expansion} = 0$ within the well after maintaining $Q_{out} = Q_{in}$.

This influx cessation may take an arbitrary period. Bacon et al. [22] studies could not approximate the time to stop the influx of compressible flow. This methodology needs to be investigated thoroughly for different mud rheology, reservoir fluid composition, operating pressure, and temperature.

5.2 MPD kick response decision tree

A decision tree expresses simplified decision-making criteria during drilling for several alternative solutions based on the available equipment and resources. Davoudi et al. [45] designed a basic decision-making response algorithm for MPD, as shown in Fig. 9.

This decision tree is based on the currently available flowmeters and other industrial equipment. Accurate flow detection is the key concern of this decision tree. Based on a positive flow check, Davoudi proposed an MPD mud pump shutdown schedule, increasing casing pressure and completely shutting down the well to mitigate the influx. Different researchers [45, 95, 171] proposed several alternative responses to kick other than a conventional shutdown, with different algorithms. They proposed decision trees and algorithms to select the initial response to kick from a set of alternatives. These decision trees can be used during the planning phase of a drilling program, which is based on the well configuration, available equipment, desired kick tolerance and decisions about the kick warning signal. The goal of their work is to select the best response during the planning phase that would give the maximum kick tolerance with available resources, well geometry and a given operating condition. Table 12 shows a comparison of different kick response scenarios. Based on the comparison, it is evident that no single proposal seems widely applicable as a comprehensive response to kick.

5.3 Risk evaluation

An appropriate risk analysis is adopted as a mitigation tool for any unwanted situation during a drilling operation. Risk analysis is a crucial tool to develop strategies to prevent accidents and develop an appropriate mitigation plan. Risk analysis serves in two ways. It determines the acceptable risk and identifies the major contributing risk factor. Once the risk factors identified, a preventive measure can be evaluated for each risk factor. Table 13 shows the category of a blowout and its consequence.

Different risk analysis method in the drilling operation such as Bow- tie approach, Bayesian network are available in the literature. Bow Tie Approach [88, 97, 98, 169] enable the breakdown of entire systems from root cause to the final consequences. A general bow-tie model considers basics events, intermediate events, top events, safety barriers and consequences. A graphical bow-tie model is helpful for the visualization of risk assessment. Though the bow-tie model is simple to use; however, the application of this failure analysis is limited to complex system due to common cause of failure and conditional dependencies on other events.

Bayesian network (BN) [3, 97, 99, 134, 177] is also used as a prominent drilling risk analysis tool in recent years. A Bayesian network begins with node, arcs, and

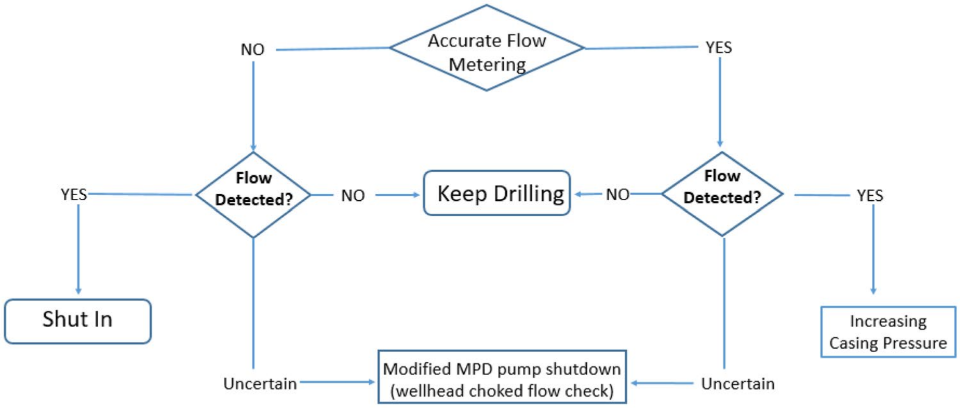


Fig. 9 Simplified algorithm of MPD kick response. Redrawn from Davoudi et al. [45]

Table 12 Alternative response to kick proposed by different authors

Researcher	Davoudi et al. [45]	Smith and Patel [171]	Karimi Vajargah and van Oort [95]
Response type	Circulating and non-circulating	Circulating	Circulating and non-circulating
Increasing/modify mud pump rate	√	√	√
Increase annular backpressure	√	X	√
Conventional shutdown	√	X	√
Evaluate change in mud weight	X	√	X
Evaluate casing pressure	X	√	√
Response to increase in casing pressure	X	√	√
Response beyond kick tolerance limit	√	X	X
Depends on flowmeter accuracy	X	√	√
Response to kick due to lost circulation	X	X	√
Algorithm for early kick detection	X	X	√
Monitor flow, pump pressure, pit gain, fluid loss etc.	X	X	√
Response depends on other drilling uncertainties	√	X	√

√ yes, X no

Table 13 Category of blowout consequences [88]

Index	Consequences	Description
1	Near Miss	Event that does not result in actual loss but has potential to do so
2	Mishap	Event that causes minor health effects and/or minor effects to property and environment
3	Incident	Event that can cause considerable harm or loss
4	Accident	Event that may cause one or more fatalities or permanent major disabilities
5	Disaster	Event that can cause multiple fatalities and extensive damage to the property, system, and production

corresponding probability functions to produce a set of random variables and provisional dependencies among them.

5.4 MPD decision matrix for well control

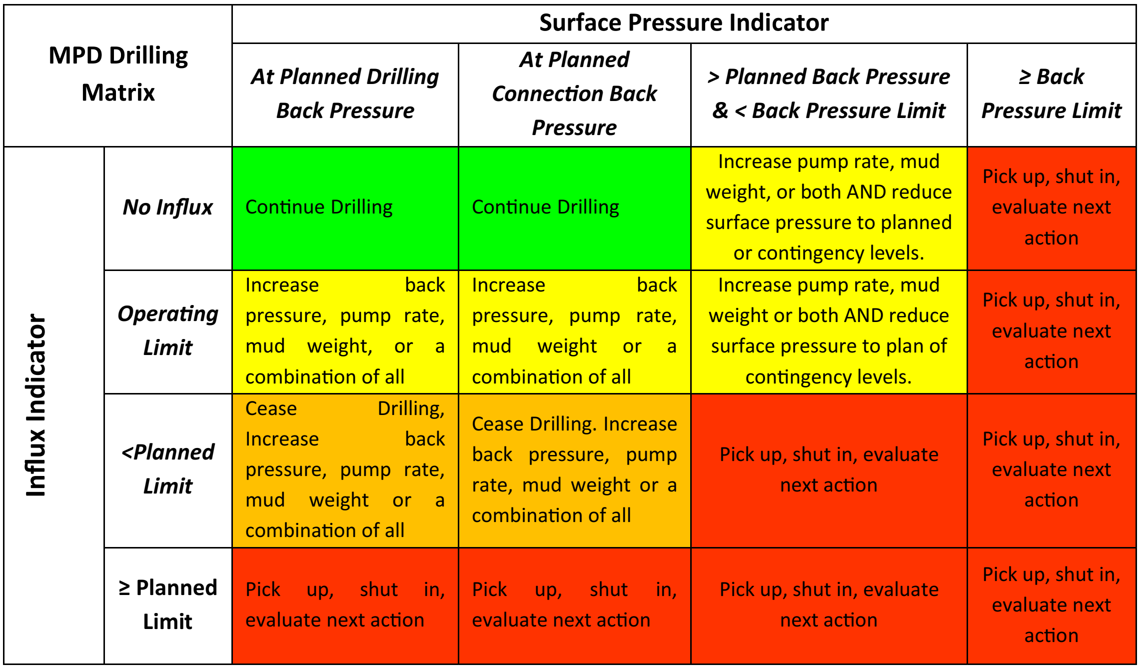
A well control matrix can perform as a substitute of the decision tree. A well control matrix helps the drilling crew to take an instant decision to continue drilling within a safe operating window. It allows a well control system to switch from dynamic well control to conventional well control methods when required. The IADC MPD [121] subcommittee also proposed a Well Control Matrix (WCM) as a guideline for CBHP MPD well control.

Well control matrix explains the proper action to maintain the primary barrier of the system, influx management and enable the transfer to the secondary barrier, such as well control, when necessary. Table 14 shows a sample well control matrix. Several studies [21, 42, 83, 149, 163, 184, 194] also proposed a variety of simplified well control matrices to control the flow, influx management, and provide a guideline for well control within safe operational limits.

5.4.1 Kill method

Several studies [83, 122, 149] proposed MPD operation and kill methods based on the influx gain ranging from 0 to 10 bbl. Different operating envelopes at different hole sections were proposed for different levels of pit gain with a variety of conditions like drilling, pump off, connection etc. A proper selection of mud weight and mud pump rate are critical during a killing method.

Table 14 Sample MPD operation matrix [121]



MPD Drilling Matrix		**Surface Pressure Indicator**			
		At Planned Drilling Back Pressure	***At Planned Connection Back Pressure***	***> Planned Back Pressure & < Back Pressure Limit***	***≥ Back Pressure Limit***
Influx Indicator	***No Influx***	🟩 Continue Drilling	🟩 Continue Drilling	🟨 Increase pump rate, mud weight, or both AND reduce surface pressure to planned or contingency levels.	🟥 Pick up, shut in, evaluate next action
	Operating Limit	🟨 Increase back pressure, pump rate, mud weight, or a combination of all	🟨 Increase back pressure, pump rate, mud weight or a combination of all	🟨 Increase pump rate, mud weight or both AND reduce surface pressure to plan of contingency levels.	🟥 Pick up, shut in, evaluate next action
	<Planned Limit	🟧 Cease Drilling, Increase back pressure, pump rate, mud weight or a combination of all	🟧 Cease Drilling. Increase back pressure, pump rate, mud weight or a combination of all	🟥 Pick up, shut in, evaluate next action	🟥 Pick up, shut in, evaluate next action
	≥ Planned Limit	🟥 Pick up, shut in, evaluate next action	🟥 Pick up, shut in, evaluate next action	🟥 Pick up, shut in, evaluate next action	🟥 Pick up, shut in, evaluate next action

6 Recent advancement and scope of future work on MPD

Though the oil industry has adopted MPD for a decade, still there are some scopes for further improvement in MPD. The following section discusses some scopes of work for MPD advancement.

6.1 Application of machine learning

Machine learning, a subclass of Artificial Intelligence (AI) is a popular tool in well control and kick management systems. Machine learning uses a different mathematical model on a sample data point or "training data," the model about the system and its response. Once the training points are established, they can be used to make a prediction and decision-making tool. In recent years, the oil industry widely used machine learning and data-driven solution like fuzzy logic, support vector machine and artificial neural network [13].

In a drilling system, inputs are mud weight, fluid viscosity, drill pipe rotation, weight on bit, rate of penetration, and ECD; whereas the output can be cuttings return rate, return mud flow rate, return gas volume fraction etc. Once the ANN model developed for a given data set, it can be utilized to generate output for an unknown input. ANN used in the different aspects of a drilling operation. In recent years, ANN used in drill bit selection [16, 25, 64, 114], dynamic behaviour of non-linear drilling system [44], troubleshooting [6, 107, 141], wellbore instability [139], ROP estimation [124], lost circulation [12], fluid rheology, hydraulics [2, 7, 51, 60, 195] and managed pressure drilling operation [9, 10, 150, 207, 209].

6.1.1 Measured data quality

Each system in a drilling operation like hook load, rotary speed, flow rate, standpipe pressure, mud pit volume etc. generate a vast amount of real-time drilling data. However, Ashok et al. [18] studies show doubt about the collected drilling data. The deviation of measured data from their accepted values must be estimated to ensure useful representative data. Automated data validation tools can be used to achieve this. Another corrective measure can be taken once a source error is detected. Artificial Intelligence (AI) and machine learning tools like Artificial Neural Network (ANN) [137, 187], data clustering [138] can be applied to rectify the large volume of data and any outlier involved in the collected data. Raw drilling data should be filtered, cleaned and combined with available drilling performance equations to measure the drilling performance [173].

6.2 Wellbore geometry

The impact of wellbore geometry [120, 178] is crucial to model a gas kick and kick response during the MPD operation. Rostami et al. [155] and Tian et al. [186] studied parametric analysis of MPD hydraulics. They have shown that the wellbore geometry, hole size and drill string arrangement have an impact on hydrodynamic friction and hydrostatic pressure loss calculation. For a slanted or deviated well, a proper simulation study can predict the kick warning, considering appropriate MPD hydraulics.

6.3 MPD in HPHT well

High pressure and high temperature (HPHT) can affect mud rheology and properties actively and hence impact the well control as well [19, 24, 52, 65, 174, 206]. Excellent thermal stability of drilling mud is required [203] for an HTHP well. Past studies show that oil-based drilling mud provides an excellent solution to thermal stability compared to the water-based drilling mud for an HTHP well [162, 204]. Oil-based drilling fluid is widely used for HPHT well [27, 36, 157] though gas kick detection with oil-based mud is more difficult to detect. The multiphase flow behaviour for a water-based mud shows a significant difference compared to an oil-based mud. The gas solubility in an oil-based mud is increased with an increase in pressure. The gas influx from the formation dissolved into the oil-based mud as solution gas, which indicates a low pit gain on the surface. This gas suddenly expands near the surface when wellbore pressure drops significantly may lead to an uncontrolled blow out situation. Predicting the temperature and pressure distribution along the wellbore is more complicated while drilling in an HPHT well with oil-based mud.

Several studies [27, 55, 87, 188, 201] proposed models for the prediction of pressure and temperature modelling in HPHT well. A temperature modelling should include the rheological, thermophysical properties of drilling mud. In addition to a wide range of physical properties of influx fluid, e.g. pressure, temperature, and specific gravity can be considered. The typical measurement of downhole pressure needs to be adjusted for HPHT well due to fluid expansion and compression for high pressure and temperature.

6.3.1 Solubility of gas in OBM, SBM

During gas kick modelling, one of the critical assumptions is that gas enters from the formation into the wellbore as a single bubble and remains the same along the wellbore. The solubility of this gas or bubble in synthetic-based mud (SBM) and oil-based mud (OBM) [112] is often ignored in gas rise velocity calculation for the simplification purpose. Nickens [135] showed that the pressure calculation of a single bubble is always higher than anticipated. In non-aqueous drilling mud like SBM or OBM, the solubility of the gas in drilling mud is not uniform. So, the gas solubility is a significant concern and cannot be ignored [110]. Therefore, proper kick detection time and pit volume may vary based on mud characteristics. Most of the recent studies on MPD are based on water-based mud and ignore the solubility of a gas in the drilling fluid. Karimi Vajargah and van Oort [95] only described a simple correlation of pit gain in SBM. For a rigorous MPD gas kick model, the solubility of the gas bubble in oil-based mud needs to explore.

6.4 Transient pressure response

Bacon et al. [22] introduced a dimensionless, transient parameter known as the 'Pressure Transfer Parameter' (PTP), which provides the BHP response on the WHP in a dynamic well control system. This PTP can significantly improve current MPD operations and well control systems regarding influx sizes and reduce surface backpressure. This parameter can be a good kick indicator for the compressible influx. Therefore, a comprehensive early kick detection model can be developed by incorporating PTP in MPD operation.

6.5 Pipe rotation and buckling

Pipe eccentricity and rotation influence fluid transition from laminar to turbulent flow. These also influence annular pressure calculation. Erge et al. [53] presented a mathematical model to incorporate these effects in calculating the bottomhole pressure during MPD. The effect of drill pipe rotation and drill pipe buckling, and eccentricity need to be investigated thoroughly to evaluate the kick in MPD.

6.6 Computational fluid dynamics (CFD) of annular profile

Computational fluid dynamics (CFD) [143] and numerical modelling [109] of annular pressure profile and wellbore geometry can provide insight into the annular behaviour of MPD. CFD can be used to simulate the kicking behaviour, influx distribution, annular pressure loss, and fluid rheology. CFD analysis can also deal with pipe eccentricity and the pipe rotation effect during drilling. Illustration of lost return in the fracture by CFD can demonstrate the behaviour of a gas kick during lost circulation.

6.7 Sour formation

Offshore carbonate formation at an HPHT [34, 67] zone is defined as sour gas reservoir, which also has a narrow drilling window. Any fracture in the sour gas formation causes the gas to invade the well easily and stimulate dangerous gas kicks [34, 156]. Conventional managed pressure drilling cannot fully satisfy the operating condition in high-pressure sour formations. Also, lost circulation may cause a kick in the sour formation. Traditional methods cannot be applied for controlling the bottomhole pressure in this type of formation. In this case, an alternative is necessary to estimate the bottomhole pressure.

6.8 Mud logging

Real-time mud logging gives valuable information about the formation and a blowout. A kick can be estimated from continuous log analysis for return mud and fluid composition [5, 8, 28, 47]. Logging data identifies a change in the behaviour of formation before a kick happens. Utilization of real-time mud logging data with a gas kick model helps to improve the available kick response behaviour.

6.9 Gas hydrate effect

Drilling in unconventional formation like gas hydrate brings up new challenges to the drilling industry. Gas hydrates are known as solid crystalline substances where a large amount of methane is trapped within the crystalline structure of the water, forming ice or ice-like substance. Drilling in a gas hydrate formation generates cuttings with gas hydrates. Decomposing gas hydrates from cuttings can produce a large amount of gas in the annulus section due to a change in temperature and pressure as proceed to the wellhead, which might cause a gas kick [61, 199].

Any kick from the gas hydrate formation may comprise of a mixture of solid, gas and liquid flow [106, 197]. Hydrates dissociation during drilling operations can cause wellbore instability. Also, there might be hydrate formation in the BOP, wellhead and choke like while circulating a gas kick from the wellbore [125]. Many researchers [61, 106, 179, 197, 199] investigated the gas kick behaviour for a hydrate formation considering a multiphase flow behaviour. However, in-depth research on gas hydrate kick modelling still needs attention from the researcher.

7 Conclusion

Conventional overbalanced drilling is not always feasible when drilling in critical reservoir conditions and narrow drilling windows. Managed pressure drilling offers a technical solution to the petroleum industry to explore complex geological formation. Early kick detection plays a vital role in offshore MPD, where kick volume tolerance is crucial. In this manuscript, environmental variables for gas kick and different kick detection methods discussed systematically. However, considerable uncertainty is involved in kick warning sign in terms of reservoir type, geological nature, drilling depth and orientation. This study summarized different early kick detection warning signs with their significance level. In any drilling operation, the response to kick should be appropriately stated based on the kick intensity and propagation rate along the wellbore. Different responses to kick and kick mitigation algorithms for MPD are systemically analyzed in this study. Several alternative responses to kick during MPD are available, but each response to kick has its limitations. Four responses (i.e. shut-in well, modified pump shutdown method, increasing casing pressure, and increasing the pump rate) are to be more efficient than others. Researchers proposed different decision- making trees for kick response; however, a single decision-making criterion for kick response cannot be applied in all drilling environments. Therefore, this work suggests further improvement in managing kick response behaviour. Finally, this work summarizes recent progress and scope for further studies in the drilling methods. Future research should focus on the recent progress of advanced machine learning methods, and geologically challenging HPHT well and hydrate reservoir. A CFD study can be used to simulate gas kick behaviour in the wellbore at the different drilling conditions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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