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Identification of well breathing phenomena in HPHT wells and technical solutions to enhance drilling efficiency in the Nam Con Son Basin



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ABSTRACT

The Nam Con Son Basin is considered the most technically challenging area for drilling operations in Vietnam and ranks among the most complex globally. Its central region, dominated by high-temperature, high-pressure (HPHT) conditions, accounts for approximately 70÷80% of the basin's total gas production. This area is geologically characterized by heterogeneous stratigraphy, abnormally high formation pressures and temperatures, and a narrow margin between pore pressure and fracture gradient-commonly referred to as the "narrow pressure window." Under such conditions, even minor variations in mud weight can lead to wellbore instability or formation damage. One of the most critical drilling challenges in this environment is wellbore breathing - a transient loss and subsequent return of drilling fluid-typically observed in formations within the Miocene formation. These formations exhibit low porosity, low permeability, and elastic rock behavior, which can result in misleading well control indications, non-productive time, and potential well control incidents if not identified and managed appropriately.

This study presents a novel diagnostic framework for recognizing and managing wellbore breathing in HPHT wells of the Nam Con Son Basin. It systematically evaluates operational data from recent wells using four key indicators: (i) loss circulation behavior during circulation, (ii) mud-volume return after pump stoppage, (iii) downhole pressure variations, and (iv) changes in total gas and gas-peak composition in returns. The combined indicators reliably identified early breathing onset and severity, distinguishing it from other circulation anomalies. Field validation confirmed the method's robustness across multiple well sections.

Applying the proposed framework, along with mud-weight optimization, real-time monitoring, and wellbore strengthening, reduced non-productive time and minimized well-control false alarms. These outcomes demonstrate significant practical value for improving safety, integrity, and efficiency in complex HPHT drilling environments worldwide HPHT.

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1. Introduction

The Nam Con Son Basin comprises multiple petroleum blocks, with geological characteristics varying significantly across the region. The structural features located along the basin margins - including Blocks 04.1, 04.3, 12/11, 12W/E, 11.2, and 06.1 - generally exhibit stable geological conditions, with conventional reservoir pressures and temperatures. In contrast, the central portion of the basin-encompassing key structural accumulations such as Thanh Long, Tho Tinh, Hai Thach, Moc Tinh, Sao Vang, Dai Nguyet, and Ngan Ha, predominantly situated in Blocks 05.1, 05.2, and 05.3 - was deposited in a shallow marine environment and is subject to the influence of complex fault systems and distinctive sedimentological regimes.

1.1. Technical challenging and the Non-productive time (NPT) for drilling operations in HPHT wells

The Nam Con Son Basin is considered the most challenging and geologically complex area for drilling operations in Vietnam. As a result, exploration drilling activities in this basin commenced relatively late, especially in prospects located in the central part of the basin such as Thanh Long, Tho Tinh, Hai Thach, Moc Tinh, Sao

Vang, Dai Nguyet, and Ngan Ha where geological conditions are characterized by highly heterogeneous lithology and high-temperature, high-pressure (HPHT) reservoir. The first well was drilled in the 1990s. Since then, more than 40 exploration, appraisal, and production wells have been drilled to date.

Due to the complex geological conditions and the presence of HPHT prospects situated in water depths ranging from 100÷200 m, both jack-up and semi-submersible rigs have been employed for drilling operations in the Nam Con Son Basin. However, technological limitations in earlier decades constrained the effective application of advanced drilling techniques for HPHT wells. Consequently, the non-productive time (NPT) recorded in wells drilled prior to the year 2000 may not accurately reflect the actual well conditions or operational challenges. Within the scope of this paper, the author focuses on compiling and categorizing the major technical issues encountered in 17 of the most recent HPHT wells drilled through the Miocene formation in the central of the Nam Con Son Basin. The consolidated data for non-productive time are presented in Figure 1 below.

Based on non-productive time (NPT) data from HPHT wells in the basin, well breathing accounts for only approximately 8% of the total

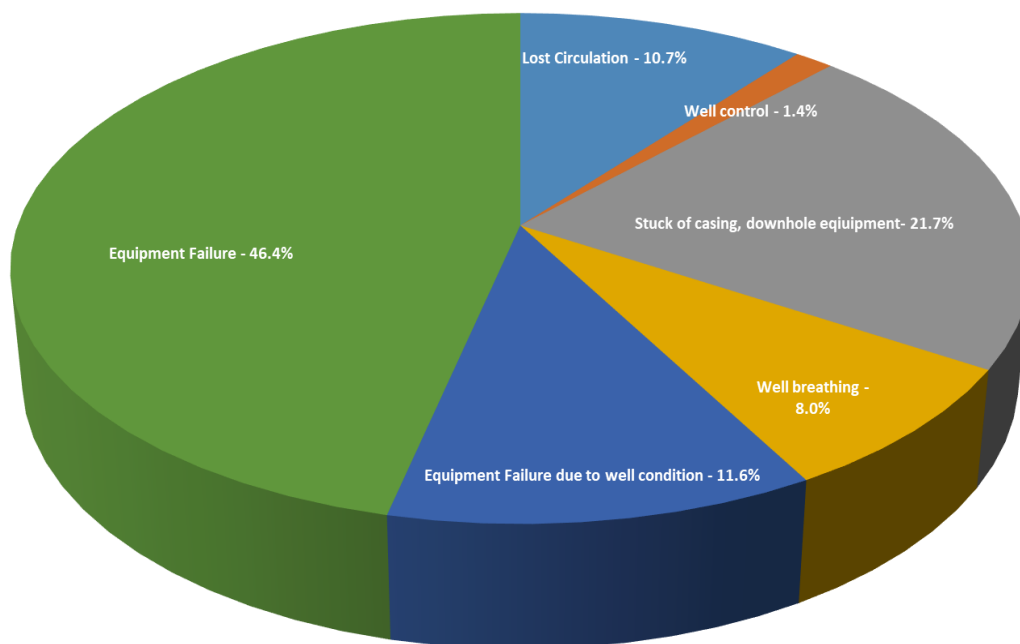


Figure 1. Non productive time in HPHT wells in the center area of Nam Con Son basin.

recorded NPT. However, if well breathing is not properly identified and managed, it can lead to significant wellbore instability and, in severe cases, result in the inability to reach the planned total depth (TD) of the well

1.2. Well breathing phenomena

In the early stages of field recognition, well breathing phenomena were often misinterpreted as conventional mud losses combined with reservoir fluid influx, caused by the pressure differential between formation pressure and hydrostatic pressure. Accordingly, when drilling or circulating, fluid losses were typically observed, followed by an increase in fluid returns once circulation was stopped. This behavior was initially explained as follows:

- Drilling fluid losses occurred while drilling through weak formations characterized by high porosity and permeability, or formations with a low fracture gradient in the overlying intervals, in combination with higher-pressure formations in the underlying zones.
- Increased mud returns were attributed to the possible influx of reservoir fluids (oil, gas, or water) into the wellbore, driven by the pressure imbalance between formation pressure and bottomhole pressure, potentially escalating into well control events such as a kick or blowout.

By 1986, Gill (Gill, 1986) documented well data from the Gulf of Mexico that exhibited typical wellbore breathing behavior, including drilling fluid losses during circulation and increased fluid returns when circulation was stopped. Key field observations and drilling parameters included:

- Cuttings analysis indicated that losses primarily occurred in formations composed predominantly of shales.
- Fluid losses were observed during drilling, with relatively low loss rates in the range of 30÷100 bbl/hr.
- Increased fluid returns were recorded when circulation was stopped, and well shut-in pressures on the drill pipe reached values up to 300 psi.

From these observations, Gill introduced the concept of shale formation elastion under bottomhole pressure, which leads to borehole

deformation. This mechanism was proposed as the primary cause of drilling fluid losses during circulation and fluid returns after circulation stops. Since the phenomenon was initially attributed solely to formation dilation, it was originally termed “well ballooning.”

However, this view was challenged, noting that the changes in fluid volume observed in wells of different hole sizes (12¼” and 8 ½”) and drilled interval lengths could not be explained solely by borehole elastion (Bowman, 1989; Holbrook, 1989). Their analysis suggested that the fluid volume variations were more likely due to a combination of two mechanisms: (1) borehole volume deformation and (2) fluid entry into the formation through induced fractures under bottomhole pressure.

This revision was understanding with using pressure-while-drilling (PWD) measurements to calculate changes in borehole volume and microfracture volume, and compared these with mud losses observed during circulation (Ward and Clark, 1998). In addition, studies began to consider the impact of bottomhole temperature and pressure on mud compressibility/expansion, further contributing to mud volume variations. With these insights, the terminology evolved, and from 1998 onward the phenomenon became more widely referred to as “well breathing.”

In subsequent years, additional research based on field data from various formations further refined the understanding of the phenomenon. Commonly observed characteristics included:

- The volume of mud returned when circulation was stopped was consistently lower than the volume of mud lost during drilling/circulation.
- Formations were geologically diverse, typically comprising interbedded calcareous sandstones and claystones with low porosity and permeability.
- Bottomhole pressure variations were observed when circulation was interrupted.

Using numerical modeling and different analytical approaches, these studies provided a more complete understanding of the mechanisms driving well breathing. This body of work, widely recognized in the industry (Silvio & Meng, 2021).

Based on these investigations, the volume of mud lost during circulation and the subsequent volume of fluid returned after circulation is stopped can be explained by three primary mechanisms (Silvio & Meng, 2021):

- i. Elastic deformation of the formation - strongly influenced by bottomhole temperature, where higher temperatures not only affect fluid volume changes but also make the formation more susceptible to elastic deformation.
- ii. Fluid compressibility and expansion - drilling mud volume changes in response to bottomhole temperature and pressure conditions.
- iii. Fracture aperture dynamics - variations in bottomhole pressure can alter fracture width and extent, allowing fluid migration into or out of microfractures.

1.3. Well breathing occurred in the Nam Con Son Basin

Exploration drilling activities in the central area of the Nam Con Son basin commenced in the 1990s. During the drilling of these wells, technical reports indicated the occurrence of “well breathing” phenomena. The primary observed in exploration and production wells within the Tho Tinh and Moc Tinh prospects. In addition, there are indications that similar phenomena may have occurred in several other wells; however, due to incomplete recorded data, it is not possible to conclusively identify those cases as instances of well breathing.

Because of the lack of comprehensive and reliable data, no dedicated research studies on this phenomenon have been conducted in the Nam Con Son basin to date.

Summary of well breathing occurred in both exploration and production wells in the Nam Con Son basin as below:

- MT-1X exploration well (Dao, 2015,2016)

Operations description: This is the first exploration well drilled on the Moc Tinh prospect. Utilized water based mud with mud weight 17.0ppg to drill 8 ½” hole section. At the depth of 3,402 m, a drilling break was found without any indication of abnormality. The operator decided to increase the mud weight to 18.0 ppg. Subsequently, significant mud losses were observed during circulation, and the mud gain

was found at the trip tank upon stopping circulation.

Mitigation Plan: shut in the well, check the value of Shut in Drillpipe Pressure (SIDP) and Shut in Casing Pressure (SICP), with SICP recorded at 0 psi. Circulation was resumed using 18.0 ppg mud, followed by an increase to 18.3 ppg with the addition of lost circulation materials (LCMs). However, the BHA was found to be stuck. After evaluating the low probability of successful fishing operations, the operator decided to back off the drill string and set a cement plug for sidetracking.

The total mitigation operation counted 5.5 days, with an estimated cost of approximately USD 2.6 million.

The well breathing information for the MT-1X well is illustrated in Figure 2 below.

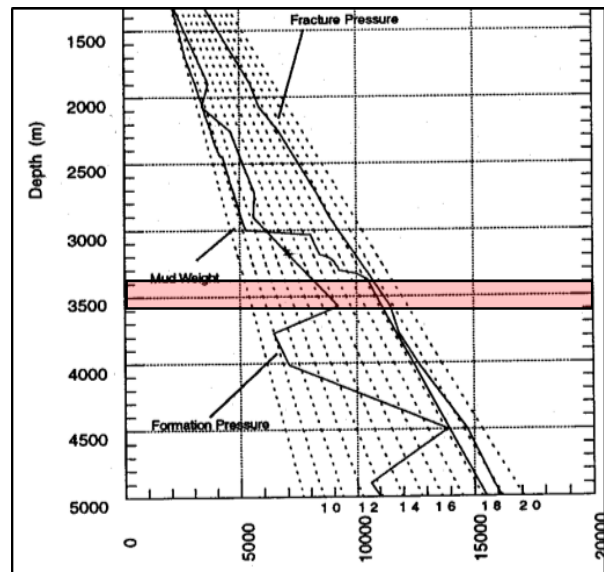


Figure 2. MT-1X well information with well breathing.

- MT-2X exploration well (Dao, 2015, 2016).

Operations description: The MT-2X well is an exploration well drilled from the Moc Tinh platform. Utilized SBM with mud weight 16.3ppg to drill 12¼” hole section. At the depth of 3,518 m, the trip tank gain of 4.7 barrels was observed.

Mitigation Plan: shut in well, check the value of SIDP and SICP; the well was subsequently opened and SICP was confirmed at 0 psi. Drilling was resumed to 3,557 m. Stop circulation and check the well static, observed pit gain with a rate of 10 barrels per hour. Continued to circulate and

well breathing has been identified as one of the major challenges during drilling operations. This phenomenon can lead to complex operational issues and potentially serious technical problems that jeopardize wellbore stability and overall drilling safety. Due to its inherently unpredictable nature, well breathing poses significant risks that affect both well design and drilling operations, as outlined below:

Impact on Well Design:

Due to the inability to accurately predict the occurrence of wellbore breathing-along with key parameters such as depth, scale, and triggering conditions-design work often encounters discrepancies. This may result in failure to meet geological objectives, shortages of essential materials or equipment, and a negative effect on overall project efficiency.

Impact on Drilling Operations:

Wellbore breathing is considered a form of operational complication or incident, which necessitates downtime for mitigation. This extends the total drilling time, especially in HPHT wells, where troubleshooting is inherently more complex. In some cases, the well may need to be abandoned, or uncontrolled flow events (blowouts) may occur, posing severe safety risks.

Impact on Project Outcomes:

Given its direct impact on both well design and operational performance, well breathing can jeopardize the entire project. Beyond endangering personnel safety and the environment, it also causes significant economic losses and undermines the overall efficiency and viability of oil and gas developments.

3. Geological conditions for wellbore breathing phenomena during drilling operations in the Nam Con Son Basin

3.1. Lithology

Within the scope of research conducted in the Nam Con Son Basin, wellbore breathing phenomena have been identified through the analysis of drill cuttings in wells that penetrate formations exhibiting distinct characteristics, including high elasticity, low porosity, and low

permeability. These formations, primarily composed of shale or sandstone with carbonate cementation, were deposited in a sedimentary environment and are predominantly located within the Middle Miocene formation at depths ranging from approximately 2,800 m TVDss to 3,600 m TVDss (Tung et al., 2011).

Due to their inherently low porosity and permeability, these formations exhibit negligible hydrocarbon reservoir potential. Consequently, conventional coring is seldom performed within these intervals, resulting in limited direct laboratory data for key rock mechanical properties such as Unconfined Compressive Strength (UCS) and other geomechanical parameters. Lithological characterization is therefore primarily derived from drill cuttings obtained during drilling operations. The lithological descriptions of formations where well breathing was observed in offset wells are summarized as follows:

Carbonate cemented shale

This lithofacies is primarily composed of a clay-rich matrix containing abundant clay minerals, interspersed with minor amounts of carbonate material and organic matter. Carbonate minerals and authigenic, light-reflecting crystals are occasionally observed over the matrix or infilling fossil voids. Additionally, the presence of a minor fraction of detrital particles-ranging from silt to fine-grained sand. These particles are mainly composed of quartz, K-feldspar, plagioclase, and foraminifera embedded within the matrix. Petrographic analysis indicates this formation exhibits very poor porosity.

Fine to very fine sandstone

These sandstones show very low porosity due to extensive infilling of pore spaces by matrix material, cement, and secondary minerals. The cement is predominantly composed of carbonate minerals. The sandstone is moderately to well sorted, consisting mainly of quartz (Q), with minor feldspar (F), lithic fragments (including granite, volcanic rock, and chert), and foraminifera (Fo). The rock is heavily cemented by calcite (Ca) and minor dolomite. The matrix material includes clay and carbonate components, with organic matter being rare.

3.2. Measure the interval of wellbore breathing occurrence

Based on offset wells data from the Nam Con Son basin and the results of wellbore analyses conducted for all of the structures within the central of basin area, a predicted pore pressure profile was developed, as illustrated in Figure 5.

Using the predicted pore pressure and fracture gradient data, a preliminary well schematic was designed, incorporating the following casing configuration: 30" x 20" x 13 5/8" x 9 7/8" x 7 5/8" liner.

The 13 3/8" casing shoe is planned to be set at the top of the Middle Miocene formation, with the setting depth ranging from 2,800÷3,200 m TVD, depending on the lithological characteristics of each prospect. Notably, at the Tho Tinh Nam prospect, the 13 5/8" casing is planned to be set at the lowest depth among the prospects, approximately 3,200 m

In the well design, the 12 1/4" hole section is

planned to be drilled through the Middle Miocene formation, from approximately 2,800÷3,600 m TVD SS, to allow setting of the 9 7/8" casing prior to penetrating the reservoir intervals.

Referred to the offset data from HPHT wells in the Nam Con Son basin in item 1.2 and the lithology descriptions in item 3.1 above. Combined with current technical standards applied in the drilling industry-including API standard, ISO standard, and guidelines for HPHT wells, the extent of wellbore breathing occurrence in the central area of the Nam Con Son Basin is defined as follows:

- **Depth Interval:** Given the lithological characteristics described above, along with the depositional environment in the central Nam Con Son Basin, wellbore breathing typically occurs in formations below the Middle Miocene Unconformity (MMU), generally within the depth range of approximately 2,800÷3,600 m TVD SS (Tung et al., 2011).

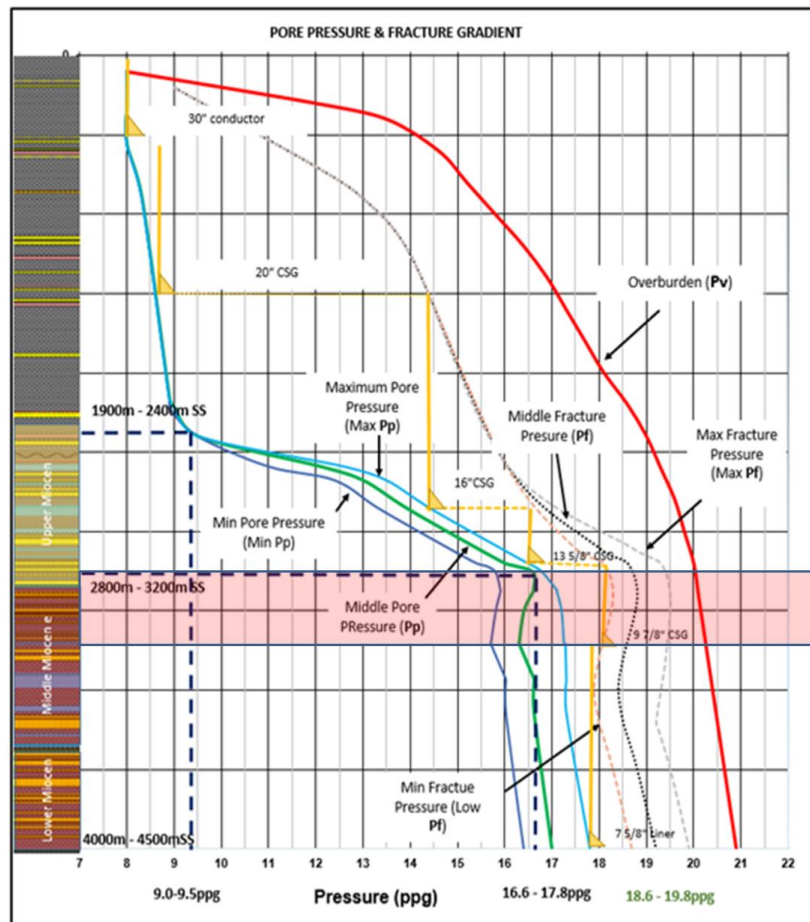


Figure 5. Predicted pore pressure and well schematic.

- *Drilling Section:* Wellbore breathing is most likely to occur during the 12 ¼" hole section is planned to be drilled through the Middle Miocene formation, from approximately 2,800÷3,600 m TVD SS, to allow setting of the 9 ⅞" casing prior to penetrating the reservoir intervals
- *Length of Breathing Zones:* According to API standards, the length of the drill stand is $L = 27$ m. In practical operations, drilling typically continues for the entire length of one stand before stopping circulation to make a connection. Consequently, the maximum interval over which wellbore breathing can be detected is 27m
- In HPHT wells, the average ROP is commonly limited to 10 m/hr, due to the requirement to compare the value of bottomhole pressure vs. formation pressure through Long Connection Test (LCT) methodology. Therefore, the typical duration in which breathing may occur is $T = 27/10 = 2.7$ hours. In cases where the ROP falls below 5 m/hr, the BHA is usually pulled for bit replacement. Therefore, the maximum expected time for wellbore breathing to be identified is $T = 27 / 5 = 5.4$ hours.
- Mud loss rate while circulating in the range of 20÷100 bbls/hr. In case of loss circulation rate >100 bbls/hr, the drilling operations must be stopped for loss circulation treatment.

Summary of drilling parameters applies for drilling section 12 ¼" section, where occurrence of well breathing phenomena as in Table 1 below:

Table 1. Drilling Parameters.

12 ¼" section	
Formation	Middle Miocene
Drilling interval	2,800÷3,600 m TVD
Mud properties	MW = 14.0÷17.0 ppg FV = 60÷80 sec PV = 33÷63 YP = 9÷13
Flowrate	600÷850 gpm
UCS	4,000÷6,000 psi
RPM	80÷150 rpm
ROP	10 m/hr

4. Indication of well breathing and measurement in HPHT wells - Nam Con Son basin

The technical data analysis for offset wells in the Nam Con Son basin, with the evaluation of drilling fluid return characteristics, it is identified that the well breathing phenomenon in the studied area can be characterized by the following four key physical indicators:

- Loss of circulation while drilling or circulating operations;
- The mud returns to the surface when the mud pump is off and circulation is stopped;
- Variation of bottomhole pressure over time during the non-circulating phase of the well;
- The mud return may contain the formation gas, leading to an increase in total gas content or gas peak composition compared to the background gas.

4.1. Mud loss while drilling or circulating

Referring to the offset data and analysis of well breathing occurrences in HPHT wells in the Nam Con Son Basin, loss of circulation is identified as the first indication of well breathing. The measurement of loss circulation shall be identified based on the following factors.

a. Mud loss volume is caused by the elastic deformation of the formation

In formations characterized by low porosity and permeability typically deposited in sedimentary environments and composed primarily of shale or sandstone with carbonate cement, the formation exhibits high elasticity. During drilling operations, when the bottomhole pressure (Pb) induced by the Equivalent Circulating Density (ECD) exceeds the formation pore pressure (Pp), elastic deformation occurs. This results in a temporary expansion of the well volume. (Feng & Gray, 2018)

Once circulation is stopped and bottomhole pressure decreases, the formation begins to return to its original state. As the wellbore contracts, drilling fluid flows back into the well, a behavior consistent with the elastic rebound effect associated with well breathing phenomena.

(Karstad, 1998). The mud loss value in this case is identified as V_e .

b. The mud loss volume into the fractures

During drilling operations, bottomhole pressure (P_b) exerts a dynamic response on the formation, following a behavior illustrated in Figure 6, consisting of four distinct stages.

Stage 1 - When the bottomhole pressure (P_b) exceeds the pore pressure (P_p) and reaches the Leak-Off Pressure value, at that time the fluid begins to move into the pores of the formation. This infiltration is facilitated by both the matrix permeability and the presence of natural fractures, in combination with the elastic properties of the formation.

Stage 2 - As drilling and circulation continue, formation cuttings generated from drilling activities are caused by increasing mud density in the hole, which in turn raises the bottomhole pressure. When P_b reaches the Fracture Breakdown Pressure (FBP) value, the natural fractures begin to open and then the induced fractures start to appear. During this stage, both natural and induced fractures are filled with drilling fluid. The volume of fluid lost varies depending on the fracture aperture, density, orientation, in-situ stress conditions of the formation, and the applied bottomhole pressure.

Stage 3 - When the well is maintained under steady-state pumping conditions, the pressure on

the formation starts to decrease. This stage is the propagation phase of induced fractures, which typically extends along the direction of least in-situ stress. As fluid continues to enter the formation, the bottomhole pressure gradually drops to the Fracture Propagation Pressure (FPP) value.

Stage 4 - Once circulation is stopped, the hydrostatic pressure at the bottomhole drops to the Fracture Closure Pressure (FCP). As a result, the previously opened fractures begin to close, and a portion of the drilling fluid that had entered the fractures returns to the wellbore, leading to what is commonly observed as well breathing behavior. The volume of mud loss into the natural fractures and induced fractures is defined as V_f .

c. The calculation of mud loss volume for well breathing

For formations belonging to the Thong Mang Cau Formation, the lithology is primarily composed of carbonate-rich shale and fine to very fine-grained sandstone, deposited in a shallow marine to deltaic environment. These sediments are dominated by matrix-supported material. Due to the influence of elevated thermal conditions, natural fractures are present within this formation; however, the fracture system is relatively limited in scale and does not exhibit

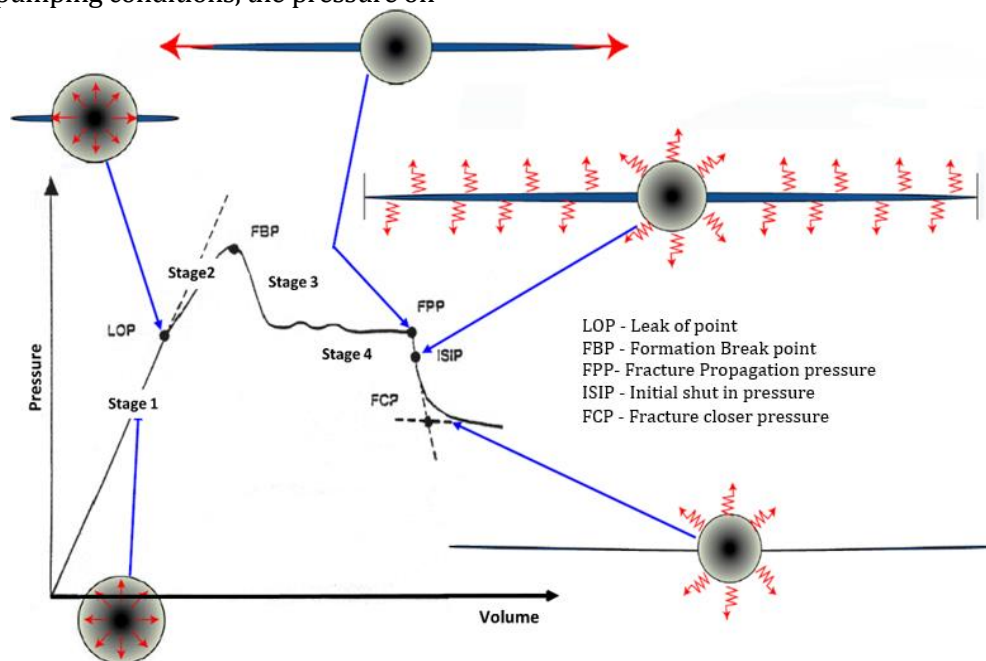


Figure 6. Pressure response of formation during drilling operations.

connectivity with a larger fracture network. (ROSNEFT, 2018).

Results from wellbore geophysical logging have been obtained from exploration, appraisal, and production wells in the central area of the Nam Con Son Basin. Imaging log data (e.g., FMI and Sonic) from wells drilled in the Tho Tinh, Hai Thach, and Moc Tinh structures reveal the presence of secondary fractures within the well breathing interval, typically observed between 2,800 m and 4,500 m TVD SS. These induced fractures approached a Northwest-Southeast (NW-SE) orientation. A pronounced East-West (E-W) fracture trend has also been observed in the logging data. In contrast, only a limited number of fractures with Northeast-Southwest (NE-SW) and Northwest-Southeast (NW-SE) orientations were identified (Scott, 2023).

The induced fractures are interpreted to be drilling-induced tensile fractures (DITFs) caused by elevated bottomhole pressure during drilling operations.

The SADE simulation model has been applied to estimate fluid loss volumes based on theoretical foundations, identifying two primary mechanisms responsible for fluid losses:

- Ve - Fluid volume lost due to the elastic response of the formation along the wellbore;
- Vf - Fluid volume lost into fractures, including natural fractures and induced fractures

In that paper, the authors used the Image log results from a well in the Nam Con Son basin, as presented in Figure 7, for input data for the SADE simulation, as Table 2 below.

Table 2. Key parameters for nature fractures & drilling induced fractures.

Descriptions	Nature Fractures	Drilling induced fracture
Total count per interval m	6 per 10 m	5÷10 per 10 m
Fracture aperture	0.1÷1 mm	0.2÷0.8 mm
Height	0.5÷2 per fracture event	1÷3 m per fracture event
Fracture spacing	2÷5 m	2÷3 m
Porosity fraction due to fractures	0.1÷0.5 %	1.0÷2.5 %
Poisson's ratio	0.30 ± 0.03	
Young's modulus	15÷25 GPa	

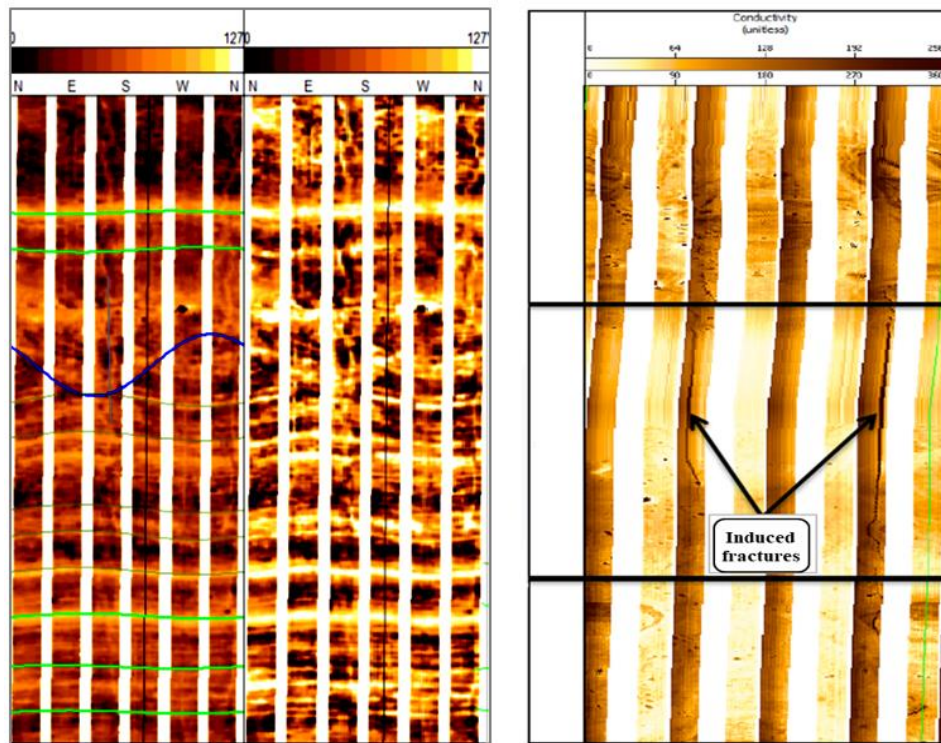


Figure 7. The nature fractures and drilling-induced tensile fractures.

Combined with actual drilling data, the well breathing zone was identified within the depth interval corresponding to fracture heights between 1 m and 27 m, with mud weights in the range of 14.0÷17.0 ppg, were identified in item 3.2 above.

In addition, key physical and mechanical properties of the formation in the Miocene - particularly in the Tho Tinh, Hai Thach, and Moc Tinh prospects - were integrated into the simulation, including porosity, permeability, in-situ stress values, rock density, and resistivity measurements at depths where well breathing events are likely to occur (from 2,800÷4,500 m). Porosity and permeability values were determined and calibrated using laboratory analysis of core samples in combination with R/SCAL data (ROSNEFT, 2018).

The results of the fluid loss volume into the formation in the event of a well breathing phenomenon, as determined using the SADE simulation model, are given in Figure 8, as follows.

4.2. The mud returns to the surface when the mud pump is off

Applying the principle of mass balance and the fluid loss mechanism associated with the well breathing phenomenon, the volume of fluid returning from the formation or fractures into the wellbore can be categorized into three distinct mechanisms:

Mechanism 1 - Volumetric Deformation:

During circulation, the pressure energy generated by the mud pump system acts on both the drilling fluid and the surrounding formation, establishing a dynamic equilibrium in which part of the fluid's potential energy is stored as elastic energy within the rock. The volume of fluid returning to the wellbore due to this elastic deformation is determined by an equation that relates the lost volume to key parameters such as pressure, rock elastic modulus, and circulating fluid volume.

Mechanism 2 - Fluid Compression in Natural Fractures:

When circulation is stopped, the pressure applied by the mud pump system is no longer sustained. The energy stored within the drilling fluid trapped in natural fractures is released. This energy is converted into kinetic energy, driving the fluid back into the wellbore. The volume of fluid returning under this mechanism is influenced by the dimensions, geometry, and pressure conditions within the natural fractures of the formation.

Mechanism 3 - Variation in Aperture of Induced Fractures:

Similar to Mechanism 2, upon cessation of circulation, the removal of pump-generated pressure causes the stored potential energy to be transformed into kinetic energy. This drives fluid from the induced fractures back into the wellbore, associated with transient changes in fracture aperture during the unloading phase.

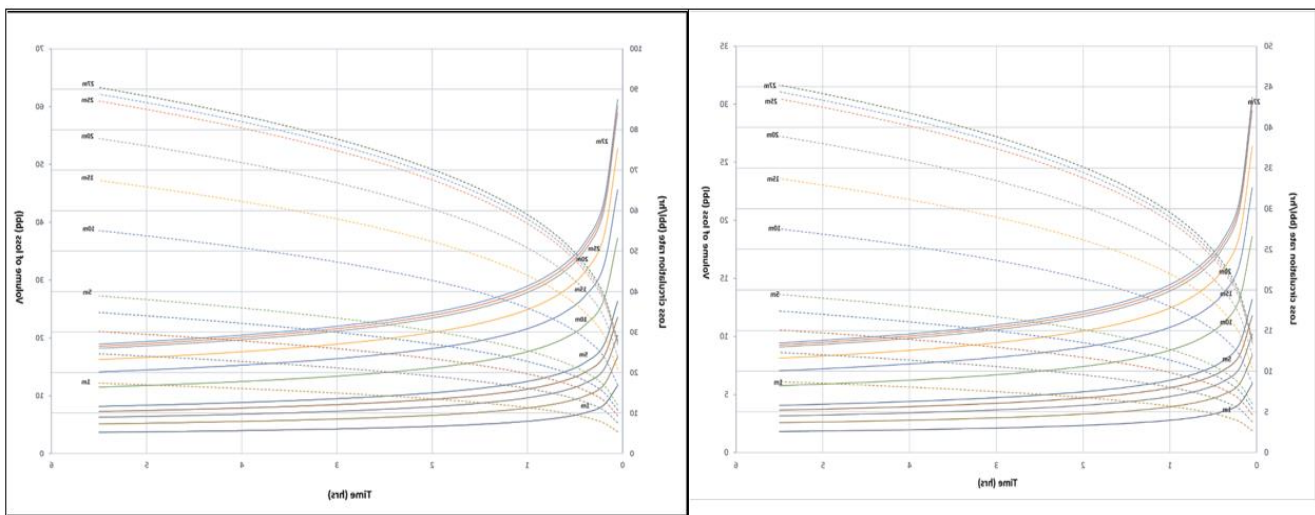


Figure 8. Loss Circulation with mud weight 14.0 & 17.0 ppg.

Using the SADE simulation model, with unit conversion factors calibrated to the operational conditions in the Nam Con Son Basin as given in item 3.2, the volume of drilling fluid returning to the wellbore was determined based on drilling parameters applied for each operational phase, as summarized in Figure 9 below.

4.3. The variation of bottomhole pressure over time during the non-circulating phase of the well

In the event that well breathing occurs, the drilling fluid will invade fractures, allowing gas to either diffuse into the fluid or exist in the form of entrained bubbles. These gas phases can then return to the wellbore along with the fluid, reducing the overall density of the mud column. (As a result, the equivalent static density (ESD) measured after circulation is stopped may decrease.

However, recorded data from wells drilled through formations within the well breathing interval in the central Nam Con Son Basin indicate that the gas content is minimal - typically less than 0.45%. Therefore, within the scope of this study, the influence of gas entrapped in natural or induced fractures on the reduction of mud density is not considered. Consequently, this effect is also excluded from the simulation models used for bottomhole pressure determination.

Based on the theoretical framework discussed in Figure 6 regarding the bottomhole pressure during drilling operations, and in conjunction with the operational drilling

parameters presented in Table 1, the SADE simulation model is applied to calculate bottomhole pressure under two conditions: (1) normal drilling conditions and (2) pressure values where well breathing occurs. The results are then compared to identify the difference between these two scenarios, enabling the detection of well breathing indicators through observable changes in bottomhole pressure values

a. Normal drilling operations condition

The bottomhole pressure values under normal drilling conditions-i.e., without lost circulation, well breathing, or other complications for 12 ¼" drilling section, using mud weight 14.0 ppg and 17.0 ppg are illustrated in Figure 10 below.

In this drilling phase, based on the operational parameters outlined in Table 1 above and a maximum mechanical penetration rate of 10 m/hr, the bottomhole pressure-related parameters were determined as follows:

- ESD (Equivalent Static Density) = 14.15 ppg,
- ECD (Equivalent Circulating Density) = 14.4 ppg

When circulation is stopped, the bottomhole pressure is calculated as:

- $P_b = ESD = 14.5$ ppg

A similar result using mud weight 17.0 ppg is illustrated in Figure 10.

In this drilling phase, based on the operational parameters outlined in Table 1 above and a maximum mechanical penetration rate of

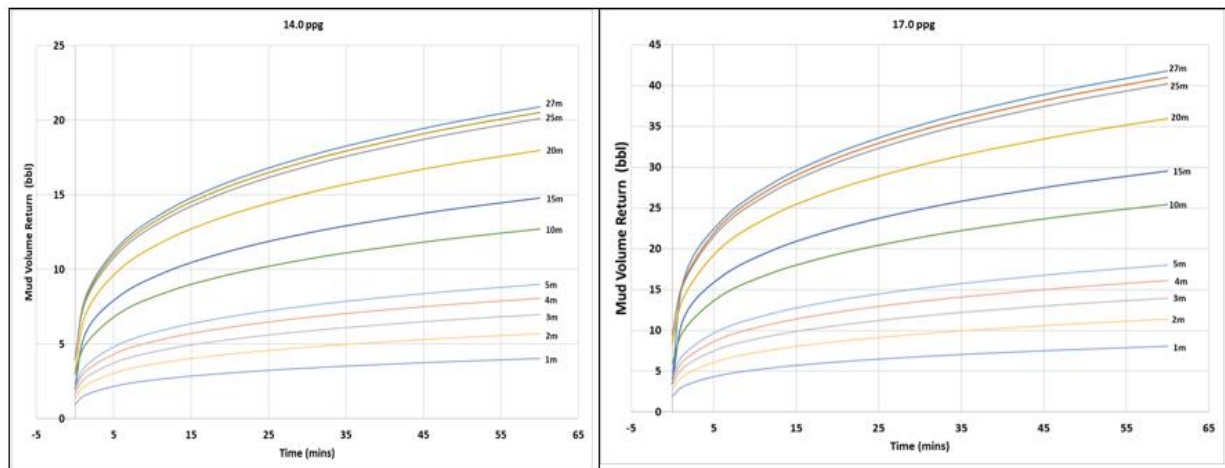


Figure 9. Volume of mud return to surface with mud weight 14.0& 17.0ppg.

10 m/hr, the bottomhole pressure-related parameters were determined as follows:

- ESD (Equivalent Static Density) = 17.18 ppg,
- ECD (Equivalent Circulating Density) = 18.25 ppg

When circulation is stopped, the bottomhole pressure is calculated as:

- $P_b = ESD = 17.18$ ppg

b. Well breathing drilling operations condition

In cases where drilling through formations and well breathing occurred, when stop circulated, drilling fluid shall be returned to the wellbore through a reverse sequence of three primary mechanisms: 1) Volumetric deformation of the formation; 2) Compression of fluid within natural fractures; 3) Variation in the aperture of induced fractures. (Helstrup et al., 2001).

Accordingly, from the moment circulation stops, the bottomhole pressure (P_b) is expressed as follows:

$$P_b = ESD + \Delta P_f(t)$$

Where: $\Delta P_f(t)$ - the pressure loss with the return flow of drilling fluid through the annular space between the borehole wall (or casing) and the drill string.

The SADE simulation calibrated with unit conversion factors properly with the drilling conditions of the Nam Con Son Basin was used to determine the annular pressure loss ΔP_f between the drill string and borehole. The resulting pressure loss values for the 12 ¼" hole sections are illustrated in Figure 11.

4.4. Changes in total gas and gas peak composition in mud return

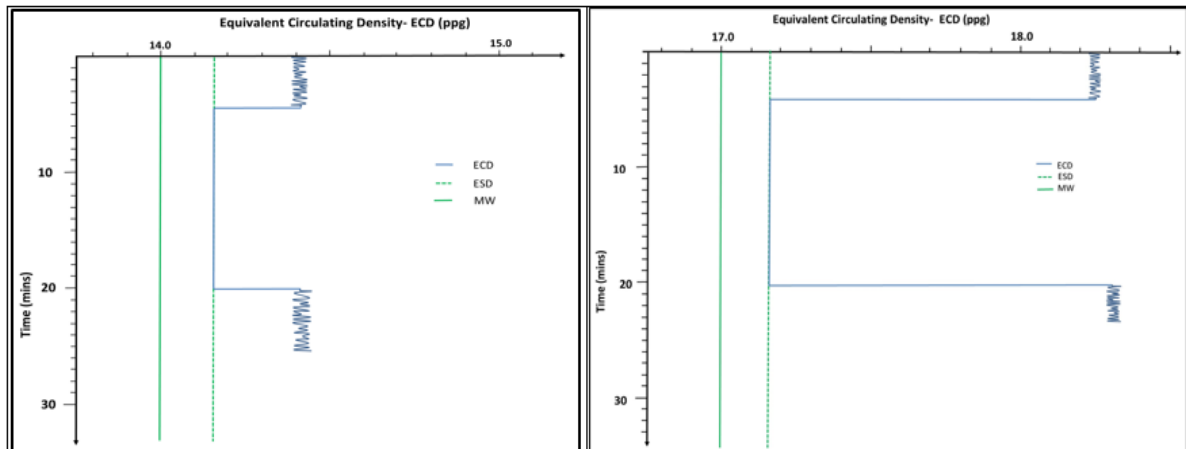


Figure 10. Bottom hole pressure when the well stop circulation with mud weight 14.0 & 17ppg.

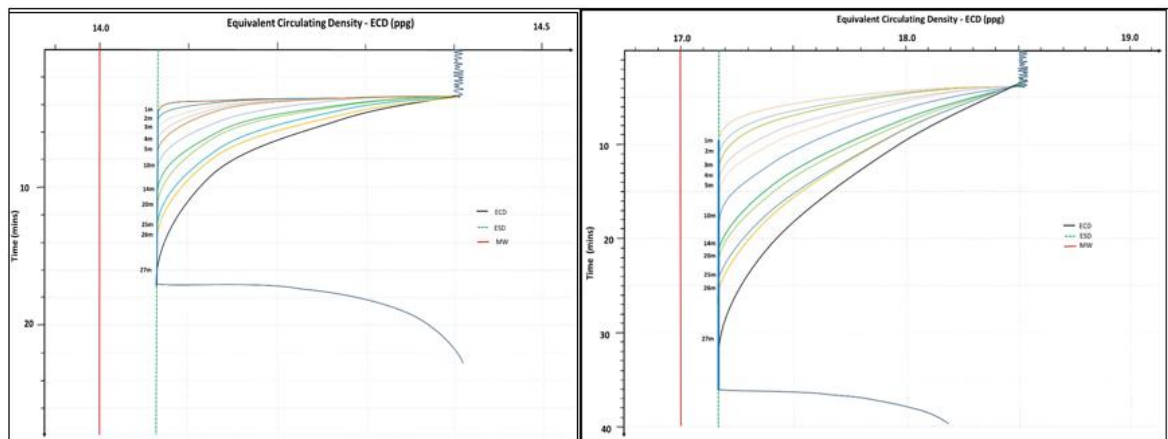


Figure 11. Bottom hole pressure when the well stop circulation with mud weight 14.0 & 17ppg.

In the HPHT wells located in the Nam Con Son basin, any abnormality of formation gas influx into the wellbore are primarily attributed to two phenomena, including 1) gas kicks and 2) well breathing. In general, distinguishing between these two events under actual drilling conditions shall be focused on analyzing two key groups of technical parameters related to the gas properties in the drilling fluid:

Total gas in the drilling fluid:

This indicator reflects the extent of gas influx and serves as a general measure of the formation's ability to release gas into the wellbore. A high level and continuous increase in this value typically suggests the occurrence of a gas kick event.

Gas peak composition in the drilling fluid:

Identifying the primary gas components enables the determination of the gas source - whether it is reservoir gas, mixed gas in the drilling fluid, or elastic rebound gas from the borehole wall. This analysis is crucial for characterizing the physical nature of the observed phenomenon and distinguishing between a kick and well breathing.

a. Total gas

During drilling operations in the Nam Con Son Basin, gas detection sensors were installed along the flowline to monitor the total gas in the drilling fluid return from the well. In the event of a gas influx, the percentage of gas in the fluid measured at the flowline increases significantly. The database was recorded in the Hai Thach Moc Tinh, Tho Tinh, and Sao Vang Dai Nguyet prospects, with average recorded values from various wells are summarized in the following Table 3.

Table 3 - Total gas in HPHT wells in Nam Con Son basin

Descriptions	Total gas % *
Conventional Drilling	0.5÷7 %
Gas influx	20÷30 %

b. Gas peak composition

In essence, due to the differing mechanisms of gas intrusion, the composition of gas present in

the drilling fluid varies between gas kick events and well breathing phenomena.

To quantify the variation in gas peak composition in the drilling fluid, two parameters are utilized: the balance coefficient (Bh) and the wetness ratio (Wr), defined by the following equations:

$$Bh = \frac{C_1 + C_2}{C_3 + iC_4 + nC_4 + iC_5 + nC_5}$$

$$Wr = \frac{(C_2 + C_3 + iC_4 + nC_4 + iC_5 + nC_5) \times 100}{(C_1 + C_2 + C_3 + iC_4 + nC_4 + iC_5 + nC_5)}$$

For Gas Kick Events:

Gas intrusion into the wellbore occurs due to a pressure differential between the formation pressure and the hydrostatic pressure exerted by the mud column. The influx typically happens over a short time interval, and gas migrates through the porous medium following Darcy flow principles. Consequently, the gas diffusion coefficient during this intrusion process is very low, resulting in negligible changes in gas composition within the drilling fluid. Therefore, both the balance coefficient (Bh) and the wetness ratio (Wr) remain relatively constant or exhibit only minimal variations.

For Well Breathing Phenomena:

When the mud loss occurred, drilling mud is gradually lost into the formation over an extended period through the three mechanisms. Under high temperature and a concentration gradient between the formation gas and the background gas content of the drilling mud, gas diffusion becomes significant. As the drilling mud loses to the formation under the influence of ECD, natural gas with primarily methane (C_1) and ethane (C_2) can diffuse into the fluid due to this concentration gradient and increase in temperature.

Experimental work conducted by Ram R. Ratnakar and Birol Dindoruk on gas diffusion into gaseous and liquid environments demonstrated that hydrocarbon gases such as C_1 and C_2 readily diffuse into the drilling mud. The diffusion coefficient increases with rising temperature and pressure (Baldino et al., 2019)

Accordingly, the natural gas diffusion coefficient into the drilling mud is expected to vary in ascending order across the following mechanisms: elastic expansion - natural fractures

- induced fractures. This results in a progressive increase in the C_1 and C_2 content of the drilling mud over time, in a reversal of the typical fluid loss pathway observed during well breathing.

When well breathing occurs, changes in gas-related coefficients are observed as follows:

B_h (Balance Coefficient): Increases due to the rising concentration of C_1 and C_2 , driven by higher diffusion rates.

W_r (Wetness Ratio): Decreases as the relative content of light hydrocarbons (C_1 and C_2) increases.

c. Measurement for HPHT wells on the Nam Con Son basin

In the measurement of changes in both total gas and gas peak component in mud return, where we could identify that well breathing occurred during drilling operations. The gas analysis data from the Tho Tinh prospect, with the well breathing occurred at the depth of 3,475 m, the gas detector used in the mud logging unit has an accuracy of $\pm 2\%$. The total gas properties in the Nam Con Son basin are given in Table 4 below.

Based on the analysis of gas properties data in the drilling mud at depths and time intervals, the following trends for gas properties were observed and illustrated in Figure 12.

- The total gas content increased (from 18.83% to 28.3%), with C_1 and C_2 concentrations rising progressively over time.
- The B_h coefficient showed a decreasing trend, while the W_r coefficient increased between the depths of 3,478 m and 3,485 m.

During drilling through the stratigraphic interval where well breathing occurred, several key indicators were identified, including losses during circulation and an increase in the volume of mud returns over time. However, the initial technical response focused primarily on treating the situation as a conventional gas kick. The changes of total gas and gas peak composition are an additional methodology for the identification of well breathing, which provides technical solutions properly.

Table 4 - Total Gas properties in Nam Con Son basin.

Influx gas	Gas Properties								
	Depth	Total Gas	C_1	C_2	C_3	iC4	nC4	iC5	nC5
	m	(%)	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FG	3460	2.5	24647	466	179	15	17	5	2
FG	3465	3.1	31052	512	210	21	22	12	8
FG	3472	3.8	37985	752	251	38	35	15	10
POG	3475	18.83	182734	5769	1780	120	203	26	15
POG	3478	22.5	220589	7426	2821	220	389	55	49
POG	3481	26.2	260548	8073	3067	239	423	60	53
POG	3485	28.6	285243	8777	3334	260	460	65	58

Where: POG - is pump off gas, recorded at the time circulation is stopped; FG - is formation gas.

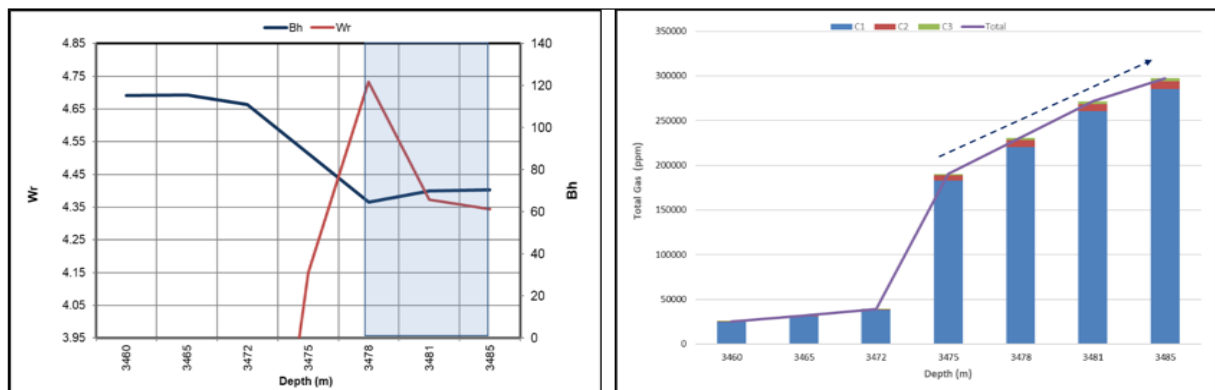


Figure 12 - Changes of gas properties in drilling mud when well breathing occurred.

4.5. Summary of well breathing phenomenon in Nam Con Son basin

Based on the analysis of theoretical factors and the results obtained from SADE simulation models for wells in the central of the Nam Con Son basin, the conclusion of the ballooning phenomenon is as follows:

Physical characteristics for identifying the wellbore breathing phenomenon during drilling operations:

- Loss of circulation while drilling/circulating
- The mud returns to the surface when the mud pump is off.
- The variation of bottomhole pressure over time during the non-circulating phase of the well
- Changes in total gas and gas peak composition in mud return

Comparison of the observed vs. simulated values as per Table 5 below.

Table 5 - Comparison between observed vs simulation.

Indications	Observed	Simulation
Loss circulation (bbl/hr)	10	2÷18
Mud return (bbls/hr)	2.7÷10	2÷42
Bottom hole pressure	The observed bottom hole pressure has not measured because no PWD was utilized in the offset wells.	The results of bottom hole pressure in a range of 5÷31 mins.
Gas composition (Wr, Bh)	The results of Bh, Wr were measured based on the observed values.	

5. Results of applying the method for identifying well breathing phenomena while drilling

During drilling operations through formations exhibiting abnormal pressure, the occurrence of well breathing is typically first indicated by minor mud losses (seepage loss rates) accompanied by a measurable gain in the trip tank volume. However, this phenomenon is often misdiagnosed as conventional lost circulation or gas influx. As a result of this misinterpretation, the standard well control procedures are typically implemented, including:

- Shut in the well using the BOP system, determine a suitable kill method, increase mud weight, and initiate circulation.
- Further actions depend on the specific well condition.

In case the well breathing is not identified, using this technical approach, the well breathing condition may worsen due to the increase in ECD, leading to more severe losses. If circulation continues, the hydrostatic pressure at the bottom hole may decrease, potentially resulting in gas influx or blowout.

With well parameters as described in item 3, the comparison of estimated response time with and without identification of well breathing phenomena is summarized in Table 6 and Table 7 below.

With the application of the well breathing identification methodology based on four (04) indications during drilling operations. In combination with formation properties measured by cutting samples. The technical solutions to mitigate the phenomenon are proposed as follows:

Table 6. Estimated mitigation durations when well breathing is not identified.

No.	Mitigation Activities	Operations duration (hrs)
1	Shut in the well, determine SIDP and SICP values, measure circulation losses volume	4÷6
2	Bleed off SICP in stages and return mud to the trip tank, monitor the change of SIDP	8÷10
3	Fully open the well, monitor well condition	2÷4
4	Circulation with lost circulation materials (LCM)	14÷16
5	Measure ECD at various pump rates. Reduce mud weight while circulating	8÷10
6	Pump cement via the bottom hole circulating tool, wait for the cement to set	10÷12
Durations (hrs)		44-58

Table 7. Estimated mitigation durations when identified the well breathing.

No.	Mitigation Activities	Operations duration (hrs)
1	Shut in the well, determine SIDP and SICP values, measure circulation losses volume	4÷6
2	Bleed off SICP in stages and return mud to the trip tank, monitor the change of SIDP	8÷10
3	Fully open the well, circulation the well with reduced mud weight and LCM	2÷4
Durations (hrs)		12÷20

- Cut back the current mud weight in combination with the use of lost circulation materials (LCM) to enhance formation integrity, allowing drilling to continue as planned; or

- Or cut back the mud weight (MW) while using a surface pressure control system MPD to proceed with drilling operations according to plan.

The estimated time required for mitigation of the well breathing phenomenon after it has been correctly identified is presented in Table 7.

For HPHT in the Nam Con Son Basin, the application of the well breathing identification methodology has yielded the following results:

- Mitigated the risk of severe fluid losses and potential gas influx.
- Minimized incident response time by at least 1.5÷2.0 days compared to conventional technical approaches.
- The implementation of optimized drilling practices has demonstrated measurable cost efficiency, yielding savings in the range of approximately 2÷3% of the total well budget for each mitigated technical event. Under the prevailing geological conditions and current service market rates, the estimated average expenditure for drilling a high-pressure high-temperature (HPHT) well in the Nam Con Son Basin with a jack-up rig is projected at 45÷50 million USD. Considering a daily spread rate of up to 580,000 USD, the avoidance of a non-productive time (NPT) event equivalent to 1.5÷2 operational days results in an estimated cost saving of approximately 0.9 million USD, corresponding to 2÷3% of the overall well cost.

6. Conclusion

Based on the theoretical analysis and the results obtained from the SADE simulation model applied for the identification of well breathing phenomenon in the HPHT wells in the Nam Con Son Basin, the following conclusions shall be considered:

- Well breathing is recognized as a drilling complication encountered in the Miocene formation. This interval is predominantly characterized by carbonate shales interbedded with fine- to very fine-grained sandstones.
- Physical indicators for identifying well breathing during drilling operations are as follows:
- Mud Losses during drilling or circulating. Drilling mud is induced into the formation under circulating pressure, with the rate and volume of losses dependent on the hole size and the mud weight applied
- The mud returns to the surface when the mud pump is off. Drilling fluid flows back from the formation once the bottomhole pressure decreases when circulation is stopped. The magnitude of this return is influenced by the hole size and the mud weight applied.
- The variation of bottomhole pressure over time during the non-circulating phase of the well. In the event of well breathing, when circulation is stopped, the bottomhole pressure decreases from the ECD value to the ESD value following a non-linear decline curve.
- Changes in total gas and gas peak composition in mud return. When circulation is stopped, gas diffuses into the drilling fluid, resulting in an overall increase

in gas content, with C_1 and C_2 concentrations progressively rising over time. This behavior can be characterized using gas property indices such as the Bh coefficient and the Wr coefficient, where Bh tends to increase and Wr tends to decrease during the circulation stop period.

With the complex geological conditions in the Nam Con Son Basin, the early identification of well breathing indicators while drilling through the Miocene formation is of critical importance. Accurate recognition of this phenomenon helps to mitigate the risk of well control incidents and other drilling-related complications, thereby enhancing operational safety and reducing overall project expenditure. In addition, the application of well breathing recognition methodologies provides a foundation for developing contingency sections in the well design, not only for this basin but also for other areas with comparable geological settings.

Contributions of authors

Tai Trong Nguyen - research idea, conception, data analysis and draft the article; Vinh The Nguyen, Richard Beaton - contribute to methodology and give a critical review during writing the first draft; Thinh Van Nguyen, Tu Van Truong - collected documents, data. All authors declare no conflict of interest.

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