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Advanced logging technologies in reservoir crossflow detection

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ABSTRACT

Crossflow exists when there are zones with dissimilar pressure properties allowed to communicate during production. Reservoir fluid from a high-pressure zone will flow preferentially to a low- pressure zone except if the production parameters are well controlled. In a multi-layer producing reservoirs, the crossflow is often related to a poor cement bonding that creates unwanted conduits behind casing. The reservoir crossflow can cause several production problems including zonal allocation, production performance and reservoir variables, potential reduction in recovery factor, and sanding problem. Several cased-hole logging tools have been introduced to detect the crossflow including Production Logging Tool (PLT), High Precision Temperature (HPT) and Spectral Noise Logging (SNL). The technology evolvement is meant to ameliorate the previous tools in crossflow detection. This paper discussed the advanced technologies in crossflow detection starting from the beginning.

1. INTRODUCTION

Crossflow exists when zones with dissimilar pressure properties are allowed to communicate during production. Reservoir fluid from a high-pressure zone will flow preferentially to a low-pressure zone except if the production parameters are well controlled. In multi-layer producing reservoirs, the fluid conduits behind casing due to a poor cement bonding often leads to crossflows between the reservoirs. Natural crossflow occurs when all layers are in hydrostatic equilibrium with each other in the absence of flow. Forced crossflow is formed when the injected layer is not in pressure equilibrium due to the injection/production activity. The pressure difference between layers is the main driving force for forced crossflow. A study by Jalali et al. (2016) on injection wells in multilayer reservoirs pointed out that the induced pressure differential and gradient begin to dissipate as soon as injection stops (that is, at well shutdown). First, the pressure gradient within the monolayer induces fluid flow from the near wellbore

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towards the far field. However, pressure dissipation through the well also occurs. This is because during shut-in, the inflow into more permeable formations reduces the pressure of the well, and the pressure in the more permeable formations can quickly become lower than the pressure in other formations. A layer with a higher pressure than the wellbore then produces fluid that flows through the wellbore into a layer with a lower pressure.

Reservoir crossflow can cause several problems. One issue is the impact on production performance and reservoir variables, such as cleat porosity and relative permeability curves, in coalbed methane (CBM) wells (Salmachi et al., 2017). Another problem is the potential reduction in the recovery factor in stratified reservoirs, particularly when high-permeability layers crossflow with adjacent low-permeability layers (Stewart, 2014). Crossflow can also lead to undesirable zonal pressure differentials and gas-oil crossflow in multiple gas-oil zonal reservoirs, requiring a reservoir management strategy to secure long-term area development (Langaas et al., 2022). Additionally, crossflow can result in sanding problems and flow from high-pressure layers to low-pressure layers in complex reservoirs (Jalali et al., 2010). This will alter the well’s injection response and may lead to perforation plugging (sand accumulation in the well) or it may plug or damage downhole equipment that controls zonal injection. In exceptional cases, crossflow can reach initial rate of thousands of barrels per day, which can even affect reservoir behaviour beyond the immediate wellbore region (Bellarby, 2009). These issues are most important in highly porous sandstone reservoirs. For example, Santarelli et al. (2000) presented a field case from the Norwegian Sea. There, crossflow and associated sand formation during shut- in condition led to massive injectability loss and complete blockage of the borehole due to liquefaction of the sand layer. Finally, crossflow between layers in a stratified reservoir can influence pressure transient well tests and other single-phase flow problems, requiring consideration of crossflow effects on pressure and the establishment of a criterion for crossflow between layers (Gao & Sun, 2017).

A study by Jongkittinarukorn et al. (2021), supported by Larsen (1981) and Kucuk et al. (1986) exhibited that analysing well test data in a multi-layer well is a difficult problem due to the complexity of interlayer flow. These issues are caused in part by a lack of data on individual layer flow into the wellbore, and in part by the mathematical consequences of commingled inflow, particularly when different layers have different skin values. Furthermore, during the shut-in period, these types of tests are frequently unable to be interpreted.

Crossflow between layers has a negative impact on data quality in conventional build-up tests from layered reservoirs, especially when the permeability contrast between layers is high. And, even when good quality data is obtained, conventional draw down and build-up tests typically reveal only the overall system behaviour (Eskandari Niya et al., 2012; Luo et al., 2014). Different reservoirs are depleted to different degrees (Jongkittinarukorn et al., 2021). As previously stated, a higher-productivity layer depletes more quickly than a lower-productivity layer with the same hydrocarbon pore volume (HCPV). Water breakthroughs usually happen faster in a shallow layer with higher productivity. Normally, we try to turn off sand that produces water. However, historical data shows that water shut-off (WSO) jobs are not very successful. The critical success factors are not well documented.

Another issue is production allocation (Al-Shehri et al., 2005). A surface production test measures the rate of production at the well level but does not account for the contributions of individual reservoirs. Reserve and productivity for each reservoir are obscured for resource characterisation (Dixon & Flint, 2010). Sand production from shallower and more productive zones can cause wellbore plugging and obstruction in some cases. This would result in a lengthy and costly well intervention and/or reserve loss. While fluid compatibility issues, which could result in wellbore scaling, should also be considered (Jongkittinarukorn et al., 2021). In a multi-layer well, there is most likely bypassed hydrocarbon (Antariksa et al., 2014; Craig & Odegard, 2008). As a result, the recovery factors of each reservoir are not maximised.

The problem that arose indicates the importance of detecting and preventing crossflows, especially in multi-layer reservoirs. Several technologies have been developed for this purpose including wireline cased-hole logging i.e. production logging, temperature, and noise logging, which will be discussed in the next sections.

2. THE EVOLUTION OF TECHNOLOGIES IN CROSSFLOW DETECTION

Detection of crossflows is mainly performed using well logging activities. In general, well logging is widely used in a mining industry (Shi et al., 2015) and oil and gas industry (Kleinberg, 2001). In the mining industry, logging is a well-established and highly cost-effective method for exploring and providing valuable mine safety information. Logging is used to identify and correlate formations within an area by using various physical properties alone or in combination with core sample analysis (Baltosser & Lawrence, 1970). Meanwhile, logging is used in the oil and gas industry to obtain a continuous record of the rock properties of formations such as lithology, porosity, permeability, fluid type, saturation, and other rock information (Crain,1986).

According to Kleinberg (2001), well logging can be defined by which physical properties of the underground earth reservoir are measured in situ. Another definition by Fanchi (2002) states that a well log can be defined as a tabular or graphical representation of all the drilling conditions or subsurface features encountered in relation to the progress or evaluation of an individual well. Well logging, also known as borehole logging, is the process of inserting a special instrument into the borehole to determine the properties of the formations around the borehole (Darling, 2005). It can be concluded that well logging in the oil and gas industry is a data acquisition methodology that lowers the logging tools in a borehole to obtain reservoir parameters within the well.

There are two main types of wirelines logging i.e. the open hole and cased hole logging. According to Felder (1994), open-hole logging refers to logging operations performed in a well before the well is cased and cemented. During drilling, the common measurement obtained from the well log, as shown in Table 1, is used to validate the predicted depth of the top of the penetrated zone and the geothermal reservoir (Dewan, 1983). Additionally, based on Timur (1982), open hole logging information is used to associate geothermal drilling with offset drilling used to study geothermal reservoirs. This data can then be used to optimise the well design of the geothermal doublet second well. Open-hole logging, in other words, is done through the bare rock sides of the formation and is a common type of logging method because the measurements are not obstructed, and it is done during or after the well has been drilled.

Through the well casing, or the metal piping inserted into the well during completion operations, is referred to as cased-hole logging (Fertl, 1984). According to Liu et al. (2018), cased hole logging helps operators obtain additional information from already completed wells or reservoirs. For example, a well may have already begun production, and cased well logs can help identify what was blocking the flow. Cased hole logs can be used not only to assess well formation and completion, but also to determine cement, corrosion, and drilling conditions (Ellis et al., 2004). Both gamma ray and neutron porosity logs as stated in Herron & Herron (1996), can be run through the casing of a well to provide better understanding of thermal decay and interval transit time through porosity, hydrocarbon saturation and producibility measurements. Consistent with Hill (2021), cased hole production logging is used to allocate production zones and diagnose production problems such as leaks and crossflows. In summary, cased hole logging is the data collection that occurs after a well is completed and provides information on casing condition, cement bond quality, hydrocarbon saturation, production flow attributes, leakage, and crossflow diagnosis.

Table 1. Common wireline logging measurement

Log type	**Formation parameter measurement**
Calliper	Hole diameter
Temperature	Borehole temperature
Self-potential (SP)	Spontaneous electrical current
Gamma ray	Natural radioactivity
Resistivity	Resistance to electrical current
Induction	Conductivity of electrical current
Sonic	Velocity of sound propagation
Density	Reaction to gamma ray bombardment
Photoelectric	Reaction to gamma ray bombardment
Neutron	Reaction to neutron bombardment

Source: Authors’ own illustration

Over the last five years, innovative methods have been introduced in the well logging technology for crossflow detection that enhanced the accuracy and efficiency of identifying fluid movement within well systems. These technologies include the combinations of neutron, sonic and temperature logging techniques as well as artificial intelligence to diagnose complex flow patterns. Orellana et al. (2019) used the integration of pulse neutron logs, cement logs, and fluid production data for diagnosing crossflow in wells. The study showed that production diagnosis (productivity, salinity, static pressures) from neighbouring wells, cased hole logs acquisition and interpretation via spectral gamma ray activation and carbon/oxygen logs as well as the integration with cement bond log, had affirm that the crossed flow fluid occurred due to commingled production between reservoir layers and possible micro channel behind cement. High-Precision Temperature (HPT) and Spectral Noise Logging (SNL) was proposed by Kalwar et al. (2024) to detect communication between tubular and annuli, identifying potential leak points and flow paths. Noble et al. (2020) suggested a new technology using unique algorithmic pattern recognition capability based on acoustic measurements from Distributed Acoustic Sensing (DAS) data, which could identify flow behind casing. In this paper the technology involving Production Logging Tool (PLT), High-Precision Temperature (HPT) and Spectral Noise Logging (SNL) will be discussed in detail for potential deployment in the future study of crossflow detection.

2.1 Production Logging Tool (PLT)

Cased hole logging is essential in the production stage of field reservoir management. The logs provide useful information for optimising the reservoir management plan and strategy, as well as the investment approach in a producing field’s lifecycle. One of the cased hole logging tools i.e. the production logging tool (PLT) includes multiple logging suites run on cased wells of production or injection wells to collect static and dynamic well data in situ for broad application in reservoir and field development planning (Shad et al., 2015). The main uses of production logging are production monitoring and assessment of fluid typing, applications for production improvement, flow, or injection well assessment, and down hole well completion diagnostics. Changes in production profile and changes in flowing liquids due to water breakthrough or gas breakthrough can be identified by deploying production logging tools (Chowdhury et al., 2019). Sheikha et al. (2020) presents a paper that interprets production log data recorded from tool

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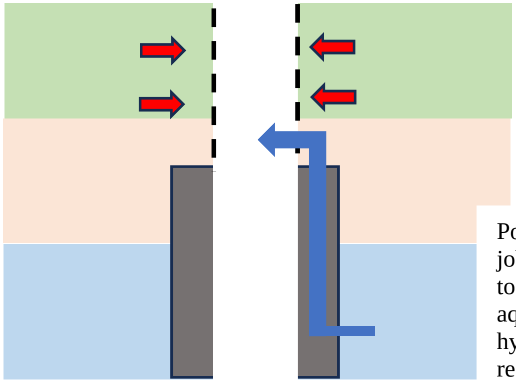
sensors to improve productivity, wells treatment strategy and identify enhanced or improved oil recovery application monitoring.

Today's advanced technology requires real-time zonal rate allocation to effectively manage well and reservoir production. Production allocation is necessary to coordinate oil, gas and water measurements at all entry and exit points of the production network. Poor allocation affects the accuracy of material balance and reservoir modelling. Allocation of production rate to individual zones through multiple acquisition modules such as velocity, phase holdup, pressure, and temperature to identify unproductive and less productive intervals and measure the relative contribution of different zones is conventionally done by running a production log suite. As the oil and gas industry progresses, more complex areas such as post-well subsea deep-water interventions for zonal allocation are commonly left out for operational economics reasons. This also applies to platform development using wells with high angle deviations (Rabie et al., 2010).

According to Taha & Amani (2019), one of the most common sources of unwanted water production is poor wellbore conditions. This type of production is typically caused by casing leaks or poor cement work behind the casings, which creates channels connecting the unwanted water production formations/sources to the wellbore. The casing and the cement job behind the casing are supposed to form a seal against such undesirable layers shown in Fig. 1.



Poor cementing job causes water to flow from aquifer into hydrocarbon reservoir layer

Fig. 1. Poor cement behind casing causing potential crossflow

Source: Illustration based on concept by Taha et al. (2019)

Many production logging surveys using a standard production logging tool have revealed that the spinner shows negative readings during the flowing condition, indicating fluid re-circulation or fluid fallback. However, data from other sensors, such as a fluid density identifier and a temperature tool, do not support these fluid re-circulation findings, resulting in an incorrect rate calculation to determine zonal contribution. To overcome this challenge, an advanced production logging tool can be used to measure the contribution more accurately for each zone as the effects of apparent downflow or crossflow are better understood. Despite the presence of apparent downflow or crossflow in the wells, the calculated production rates from the advanced production logging tool were found to be more representative (Rosli et al., 2017).

2.2 High Precision Temperature (HPT) Logging

According to Zeinalabideen et al. (2021), the temperature sensor is a platinum-wire thermistor. The sensor resistance varies with temperature, and the sensor's changing output voltage is fed into the input of an analogue-digital converter. The temperature is then calculated using a calibration procedure (Aslanyan et al., 2013). The HPT is a specially designed wireline tool that differs from the standard temperature tool that is typically used with PLT; see Table 2 for HPT tool specifications. The main issue in temperature logging today is sensor response time and depth correlation, not sensor sensitivity. The response time indicates how quickly the sensor responds to changes in fluid temperature, though tool manufacturers do not always publish this parameter. Furthermore, because the sensor's housing is not completely transparent to fluid flow, the tool's response is typically longer than the sensor's specified time response. This lengthens the time required to achieve a temperature balance between the sensor or tool and borehole fluid. As a result, the best temperature tools are designed with maximum temperature sensor exposure (Sarsekov et al., 2017).

Table 2. Specification of High Temperature Logging

Measurement type	HPT Specifications
Accuracy	0.1 °C (0.36 °F)
Dynamic range	N/A
Resolution	0.001 °C (0.0018 °F)
Pressure rating	9000 psi
Temperature rating	0–150 °C (32–305 °F)
Length	0.44 m
Weight	2.5 kg
Diameter	1.65 in

Source: Aslanyan et al. (2013)

Maslennikova et al. (2012) discussed the differences between the low-resolution conventional temperature log and the high-precision temperature log. In comparison to HPT logs, which correlate perfectly with the top and bottom of the perforated interval, the low-resolution temperature log records could be blurry. Low-quality records may depend on the tool location inside the hole and cannot even be reproduced under identical temperature conditions due to longer response times. This appears to explain why the flowing and transient temperatures can be misinterpreted as behind-casing channelings beneath the perforations.

2.3 Spectral Noise Logging (SNL)

According to Services (2017), the spectral noise logging tool is intended to record sound across a broad frequency range. A highly sensitive hydrophone, which is a piezo crystal sensor placed in an oil-filled chamber, is the key component of the SNL tool. Oil reduces the density difference between the wellbore fluid and the sensor's environment, minimising acoustic wave reflection from the interface and increasing sensor sensitivity (Volkov et al., 2018). Using high- frequency analogue-to-digital converters, the recorded time-domain data is written to the tool's internal memory. After reading the data from the tool, further analysis of SNL data is performed.

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The recorded noise logging data span a wide frequency range in the spectral domain, from 8 Hz to 58.5 kHz. The tool's battery pack can power all its electronic components for 48 hours straight. Fig. 2 shows the SNL tool diagram. The tool can be used in both vertical and horizontal wells and operates in memory mode on slickline, wireline, tractor, or coiled tubing. The tool's components are all made of high-strength materials, and its electronic circuits are built with high-temperature components. As a result, the SNL tool can survey wells at temperatures as high as 150 °C and pressures as high as 60 MPa. The titanium tool housing can be used to log wells containing hydrogen sulfide (H_2S), and the SNL's technical specifications are listed in Table 3.

Table 3. Specification of Spectral Noise Logging

Measurement type	**SNL Specifications**
Accuracy	3–58,500 Hz
Dynamic range	0 – 90 dB
Resolution	115 Hz
Pressure rating	9000 psi
Temperature rating	0–150 °C (32–305 °F)
Length	0.816 m
Weight	7 kg
Diameter	1.65 in

Source: Improvised from Zeinalabideen et al. (2021)

Fig. 2 depicts the SNL panel's noise volume distribution from less than 300 Hz (left side of the panel) to 30 kHz (right side of the panel). The colour palette begins with red for the highest noise volumes and progresses to yellow, green, and blue for lower noise volumes, with white denoting noise below the tool sensitivity threshold, and the spectra clearly show matrix flow as a noise peak (TGT Diagnostics, 2017).

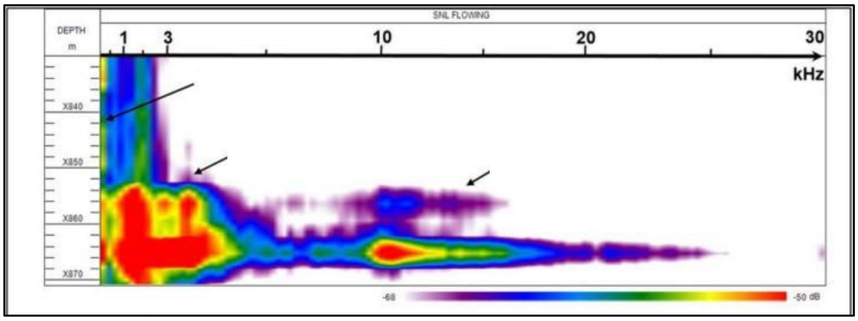

Fig. 2. SNL Noise volume distribution

Source: Improvised from TGT Diagnostics (2017)

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2.4 The PLT-HPT-SNL Logging Tool

HPT logging was reported to be used in Abu Dhabi; a developed field with over 50 years of creation history and more than 350 wells, which is one of the world’s biggest seaward oil fields (Ghalem et al., 2012). As oil fields mature, water and gas forward leaps become progressively incessant and the comprehension of smooth motion becomes urgent for legitimate supply the executives, productive healing works and ideal workovers and future wells development to improve oil recuperation. Table 4 summarises the result of the noise and high precision temperature logging intended in Abu Dhabi wells according to respective logging objectives and the results from the logging interpretation.

Table 4. Case study of PLT-HPT-SNL in crossflow detection

Case Studies	Objective	Tools	Result	References
Well 1	Crossflow detection	PLT-SNL	Crossflow detected through PLT-SNL interpretation	Ghalem et al. (2012)
Well 2	Production interval in short and long strings	HPT-SNL	Production interval in the short string quantified through static and flowing mode of HPT-SNL logging	
Well 3	Production interval and leaks detection in short string	HPT-SNL	Production interval quantified and leaks detected in the short string through HPT- SNL logging	
Well 4	Gas flow investigation in high GOR well	HPT-SNL	Gas injection identified through HPT-SNL logging	
Well A	Flow behind casing in fractured carbonate	PLT-HPT- SNL	Active crossflow behind casing detected during shut in.	Zeinalabideen et al. (2021)
Well B	Reservoir inflow analysis for injector	HPT-SNL	Low-rate injection detected by HPT-SNL. PLT misses the low injection rate due to the spinner threshold.	
Well C	Gas entry point	SNL	Detected fluid flow through reservoirs	

Source: Ghalem et al. (2012) and Zeinalabideen et al. (2021)

Based on the findings of the case studies, it is possible to conclude that HPT-SNL logging can meet the objectives of the intended wells in Abu Dhabi and Iraq, respectively, and can be used to diagnose and evaluate production performance and well injection. According to the case studies, the combination of PLT-HPT-SNL data will provide a better analysis of downhole issues and more detailed interpretation results.

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3. CONCLUSION

Reservoir crossflow detection is important because it allows fluid to pass between communicating layers, hence significantly impacting the displacement profiles and recovery factor in reservoirs. Additionally, detecting crossflow is essential for reservoir management strategies, especially in cases where zonal crossflow can lead to undesirable outcomes such as gas-oil crossflow or impairment of production. Accurate determination of crossflow in oil reservoirs is also important for numerical modelling and simulation, as it allows for more accurate predictions of pressure, flow, and fluid behaviours in the reservoir. The technologies used in crossflow detection as discussed in this paper evolved from production logging (PLT) through to high precision temperature (HPT) and spectral noise logging (SNL) tools. Nowadays, the combination of these tools i.e. PLT-HPT-SNL had shown great results in crossflow detection as reported in Abu Dhabi and Iraq. The tools can locate crossflow in fractured carbonate reservoir and in an inflow analysis for injection well.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Zaim Zakwan Zainal Abidin: Conceptualisation, methodology, formal analysis and writing-original draft; **Wan Zairani Wan Bakar**: Supervision, writing-review and editing and validation; **Tengku Amran Tengku Mohd**: Supervision, writing-review and validation.

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