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REAL-TIME MONITORING AND STATISTICAL ANALYSIS: OPTIMIZING SAND DETECTION IN OIL WELLS

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Abstract. Sand production in oil wells accelerates erosion, degrades downhole and surface equipment, and increases unplanned shutdown risk. This study presents a real-time, non-intrusive early warning workflow for sand-risk indication using routine wellhead surveillance under normal operating conditions.

Two field wells (N-1 and N-2) were monitored over a 2-hour window with 10 s sampling. Measured variables included liquid and gas flow rates, wellhead, tubing, and casing pressures, temperature, and periodic fluid-property checks (density and viscosity). A baseline was set from the first 30 min of stable operation. Alerts were triggered using a statistical rule ($\mu \pm 2\sigma$). Correlation and linear regression were applied to link pressure instability (ΔP) with flow-rate deviation (ΔQ).

The dataset shows a strong association between pressure and flow, with Pearson r up to 0.74 and regression $R^2 = 0.81$ ($n = 96$ paired points). The gas-lift well (N-2) showed higher pressure and flow variability than N-1, consistent with higher sand-risk tendency. Trace solids were observed on surface filters at concentrations below 0.1 g/L, indicating incipient sanding.

The approach forms an early warning layer based on statistically determined deviations from stable wellbore behavior and supports proactive sand control risk management without installing additional downhole control tools. This allows potential conditions for sand production to be identified at an early stage, reducing the likelihood of unplanned shutdowns and optimizing well operating modes by using readily available real-time field data.

Keywords: sand production, wellhead monitoring, early warning, statistical thresholding, pressure instability, flow-rate deviation

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НАҚТЫ УАҚЫТТАҒЫ МОНИТОРИНГ ЖӘНЕ СТАТИСТИКАЛЫҚ ТАЛДАУ: МҰНАЙ ҰҢҒЫМАЛАРЫНДА ҚҰМ ШЫҒУЫН АНЫҚТАУДЫ ОҢТАЙЛАНДЫРУ

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Аннотация. Мұнай ұңғымаларында құмның шығуы эрозиялық үдерістерді жеделдетіп, ұңғымаішілік және жерүсті жабдықтарының тозуын арттырады, сондай-ақ жоспардан тыс тоқтаулар қаупін күшейтеді. Аталған зерттеу қалыпты пайдалану режимдерінде ұңғыма сағасын штаттық бақылау деректеріне сүйене отырып, құм шығу тәуекелін ерте анықтауға арналған нақты уақыттағы инвазив емес ерте ескерту жұмыс тәртібін ұсынады.

Екі өндірістік ұңғыма (N-1 және N-2) 2 сағат бойы 10 секундтық қадаммен бақыланды. Өлшенген параметрлер қатарына сұйықтық пен газ шығындары, ұңғыма сағасының, құбырішілік және сақинааралық қысымдар, температура, сондай-ақ флюид қасиеттерін (тығыздық пен тұтқырлықты) кезеңдік тексеру кірді. Базалық деңгей алғашқы 30 минуттағы тұрақты жұмыс деректері негізінде анықталды. Ескерту сигналдары статистикалық ереже ($\mu \pm 2\sigma$)

бойынша іске қосылды. Қысым тұрақсыздығы (ΔP) мен шығын ауытқуы (ΔQ) арасындағы өзара байланысты бағалау үшін корреляциялық талдау және сызықтық регрессия қолданылды.

Зерттеу нәтижелері қысым мен шығын арасында айқын байланыс бар екенін көрсетті: Пирсон корреляция коэффициенті 0,74-ке дейін жетті, ал регрессияның анықталу коэффициенті R^2 = 0,81 (n = 96 деректер жұбы). Газлифтпен жұмыс істейтін N-2 ұңғымасы N-1 ұңғымасымен салыстырғанда қысым мен шығынның жоғары құбылмалылығын көрсетті, бұл құм шығуға бейімділіктің жоғары екенін меңзейді. Жерүсті сүзгілерінде механикалық қоспалардың 0,1 г/л-ден төмен іздік мөлшері анықталды, бұл құм шығудың бастапқы кезеңін көрсетеді.

Ұсынылған тәсіл ұңғыма дінінің қалыпты жұмыс режимінен статистикалық тұрғыдан анықталған ауытқуларға негізделген ерте ескерту жүйесін қалыптастырады және қосымша ұңғыма асты мониторинг құралдарын орнатпай-ақ, құм шығу қаупін алдын ала басқаруға мүмкіндік береді. Бұл әдіс құм өндірудің ықтимал жағдайларын ерте анықтауға, жоспарланбаған тоқтаулар ықтималдығын төмендетуге және нақты уақыт режиміндегі қолжетімді далалық деректерді пайдалану арқылы ұңғымалардың жұмысын оңтайландыруға жағдай жасайды.

Түйін сөздер: құм шығуы, ұңғыма сағасы мониторингі, ерте ескерту, статистикалық шектер, қысым тұрақсыздығы, шығын ауытқуы

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МОНИТОРИНГ В РЕАЛЬНОМ ВРЕМЕНИ И СТАТИСТИЧЕСКИЙ АНАЛИЗ: ОПТИМИЗАЦИЯ ВЫЯВЛЕНИЯ ВЫНОСА ПЕСКА В НЕФТЯНЫХ СКВАЖИНАХ

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Аннотация: Вынос песка в нефтяных скважинах ускоряет эрозию, ухудшает состояние подземного и наземного оборудования и повышает риск внеплановых остановок. В работе представлен оперативный неинвазивный алгоритм раннего предупреждения о риске пескопроявления на основе штатного устьевого мониторинга при нормальных режимах эксплуатации. Две промысловые скважины (N-1 и N-2) контролировались в течение 2 часов с дискретностью 10 с. Регистрировались дебиты жидкости и газа, устьевое, трубное и затрубное давления, температура; периодически определялись свойства флюида (плотность и вязкость). Базовый уровень задавался по первым 30 минутам устойчивой работы. Срабатывание сигналов определялось по статистическому правилу ($\mu \pm 2\sigma$). Для оценки связи нестабильности давления (ΔP) с отклонениями дебита (ΔQ) применялись корреляционный анализ и линейная регрессия. Показана выраженная связь между давлением и расходом: коэффициент корреляции Пирсона достигает 0,74, коэффициент детерминации регрессии $R^2 = 0,81$ ($n = 96$ парных точек). Газлифтная скважина (N-2) характеризовалась более высокой вариабельностью давления и дебита по сравнению с N-1, что согласуется с повышенной склонностью к выносу песка. На поверхностных фильтрах отмечены следовые количества механических примесей менее 0,1 г/л, что указывает на начальную стадию пескопроявления. Предложенный подход формирует систему раннего предупреждения на основе статистически выявляемых отклонений от стабильного поведения скважины и поддерживает проактивное управление рисками, связанными с выносом песка, без установки дополнительных внутрискважинных средств контроля. Это позволяет выявлять потенциальные условия пескопроявления на ранней стадии, снижать вероятность незапланированных остановок и оптимизировать режимы работы скважины за счёт использования доступных промысловых данных в режиме реального времени.

Ключевые слова: вынос песка, устьевой мониторинг, раннее предупреждение, статистические пороги, нестабильность давления, отклонение дебита

Introduction. Sand production is a persistent challenge in oil and gas wells, leading to accelerated erosion of surface and downhole components, increased solids handling, and frequent operational disruptions. Sand ingress can impair wellbore and surface facilities, reduce effective production time, and increase maintenance expenditures. Consequently, early identification of sand-risk conditions is critical for timely intervention and for minimizing production deferment (Ayers W.B., Belayneh M, 2009).

Accordingly, the primary objective of early sand-risk diagnosis is to support proactive mitigation actions before measurable erosion, plugging, or production impairment occurs.

However, many existing sand detection practices are reactive and identify sand only after it has already entered the production stream. Downhole acoustic tools and imaging/logging surveys can provide valuable confirmation, but they typically require additional intervention, increase operational cost, and may still detect sand after erosion, plugging, or production impairment has begun. Consequently, there is a practical need for an early-warning method that relies on routinely available surface measurements and can be implemented continuously under normal operating conditions (Carlson, 2018).

This study proposes a non-intrusive monitoring framework that uses standard wellhead indicators-flow rate, wellhead/tubing/casing pressures, and basic fluid properties–to detect statistically significant departures from stable operating behavior (Economides and Nolte, 2000). The core assumption is that sand-risk conditions are preceded by measurable instability in pressure–flow dynamics. Accordingly, the relationship between operational parameters and the sand-risk indicator is expressed as:

$$S = f(Q, P_{wp}, P_{tp}, P_{cp}, \rho, \mu) \quad (1)$$

where S denotes a sand-risk (or sand formation) indicator and f represents a multivariate mapping that aggregates changes in flow rate (Q), wellhead pressure (P_{wp}), tubing pressure (P_{tp}), casing/annulus pressure (P_{cp}), fluid density (**ρ**), and viscosity (**μ**). In the proposed workflow, S is inferred from deviation-based features extracted from these variables relative to a defined baseline, enabling early alerts when abnormal behavior is detected (Al-Anazi and Al-Majed, 2015).

The main goal of this method is to make things work better and reduce the time spent on maintenance. It does this by looking closely at ways to control sand. A lot of research and experiments have shown that this method is very good at finding out when sand is starting to form so we can take action early. Do maintenance when we need to (Aliyev and Karimov, 2020). This is based on studies and results, from peoples work. The sand control strategies are a part of this method and they help us to improve operational efficiency and minimize maintenance time by dealing with sand formation early on (He X., Pang Z., et al, 2024).

This study helps the oil and gas industry by finding ways to predict when sand will be a problem in oil wells. The oil and gas industry can use operating parameters to figure out when sand is going to be a problem early on. The main thing we learned is that taking care of sand problems before they happen is really important for making sure oil wells work well and last a long time. The oil and gas industry needs to manage sand to get the best production performance and keep their assets in good shape. Sand management is key, to the oil and gas industry.

The way sand is. Moves is really important when we are planning to produce oil and gas especially in areas where the rock is not strongly held together. When sand is produced it usually happens because the rock in the reservoir breaks down and this is caused by changes in the stress on the rock and the way fluids move around the well. If the oil and gas are flowing quickly and the pressure is dropping too fast it can make the walls of the rock around the well unstable and this allows sand to get into the well and flow through the system that produces the oil and gas. As we know when sand moves like this it can cause problems for the equipment on the surface and down, in the well which means we do not get as much oil and gas out as we could and the equipment does not last as long as it should (Kokal and Sayed, 2012). Sand production is an issue because sand can damage the equipment and reduce the amount of oil and gas that we can produce so we need to understand the mechanics of sand formation and transport to avoid these problems.

We are seeing some changes in how we can watch things in real time and predict what will happen. This is helping us to look at data all the time so we can stop problems with sand before they start. If we combine the information from sensors with math models the people in charge can start fixing things before, they break. This means they can act at the time and it is less likely that something really bad will happen. The people, in charge can move away from fixing things after they break and start taking care of them before that. This is a change and it is helping to reduce the chance of really bad things happening to the equipment that deals with sand (Matanovic et al, 2012; Xu et al, 2024).

People have been looking into fiber-optic sensing and data-driven algorithms for a while now. Fiber-optic sensing and data-driven algorithms have some points like they can tell us what is happening really quickly. They are also very expensive to set up and they need to be adjusted a lot (McPhee et al, 2015; Hasanov and Mammadov, 2021; Khalil et al, 2023).

Fiber-optic sensing and data-driven algorithms are not using the information, from the wellhead like pressure and flow rate and fluid properties to make predictions and figure out what is going on without spending a lot of money.

This study tackles a real problem-catching sand early before it causes trouble. The idea is to build a system that crunches numbers and pulls in data from sensors, so companies can spot sand issues faster. They can add this new system right into the tools they already use to keep an eye on things. With better info at their fingertips, managers don't have to just wait around for something to break. They can jump in and fix things before it gets bad. That means fewer emergencies, less damage, and fewer headaches all around. Sand detection matters, and this study is pushing it forward by making the process smarter and more reliable.

This study looks at operating parameters. It helps sand detection models work better in types of wells and reservoir conditions. The findings are useful for a field and also for the general knowledge of reservoir engineering. This means it can help people manage sand better reduce the effects, on the environment and make wells last longer economically.

Fluid movement in the wellbore is really important for oil and gas production. It affects how well the well works and the risks of sand production (Ahmed, 2010; Dusseault, 2013).

Oil, gas, and water slip out of the reservoir and into the production tubing through those perforations in the wellbore. They don't just wander in - it's the pressure difference between the reservoir and the wellbore that actually pulls them through. Without that pressure gap, nothing moves, and production stalls.

But here's the thing: all this movement puts extra stress on the rock around the wellbore. You have to think about how fluids flow inside, because it affects both the wellbore and how much oil and gas you can get out (Bourgoyne et al, 1986; Gomes and Pereira, 2017).

As the fluids head up the wellbore, gas, liquids, and sometimes solid particles all mix together, and the way they interact creates some pretty complicated flow patterns. If flow rates shoot up or pressure suddenly drops near the wellbore, the rock in the reservoir can start to break apart. Weak formations crumble, and sand gets dragged along for the ride, ending up in your production system. That sand is trouble - it wears down equipment, plugs things up, and if you don't stay on top of it, you're looking at shutdowns.

Materials and methods. We've come up with a way to keep an eye on oil wells in real time, using stats to catch sand problems early. Sand showing up in a well is a big deal—it can wreck equipment, slow production, and jack up maintenance bills. So, by constantly watching things like flow rate, wellhead pressure, casing pressure, fluid density, and viscosity, this approach helps spot sand risks before they turn into real trouble (Asfha et al, 2024).

The approach centers on several key methods:

1. High-resolution sensors are strategically installed to measure wellhead indicators, capturing pressure, flow rates, and fluid properties in real-time. Continuous data collection enables accurate monitoring of operational fluctuations that correlate with sand formation risks.
2. Statistical techniques, such as deviation analysis, are applied to detect anomalies in well parameters. Significant deviations from baseline values trigger alerts, highlighting potential sand formation events and allowing for early intervention.
3. The relationship between flow rate and pressure changes serves as a predictive factor for sand formation. Models based on principles like Darcy's Law quantify the impact of flow rate variations on pressure, linking these to sand occurrence probabilities.
4. For wells employing gas lift, pressure differentials are monitored to identify high gas content areas prone to sand formation. Tracking the dynamics of gas-liquid flow regimes helps in understanding the conditions favoring sand production.
5. Historical and real-time data train predictive models to estimate sand formation likelihood, enhancing the accuracy of early warnings. Machine learning techniques could be integrated to refine these predictions further.
6. A multivariate function aggregates deviations across well parameters, yielding a sand risk score. This risk assessment supports decision-making by indicating wells requiring immediate intervention (Hossain and Al-Majed, 2015, Zhang and Yin, 2016, Rahmati et al, 2019).

Experimental Part. This experimental study was carried out on two selected oil wells (N-1 and N-2) in real-world production conditions, with continuous monitoring of wellhead indicators over a 2-hour period. The primary goal was to observe how variations in normal operating parameters—specifically flow rate, pressure, and fluid properties-could be used to detect early signs of sand formation in the wells.

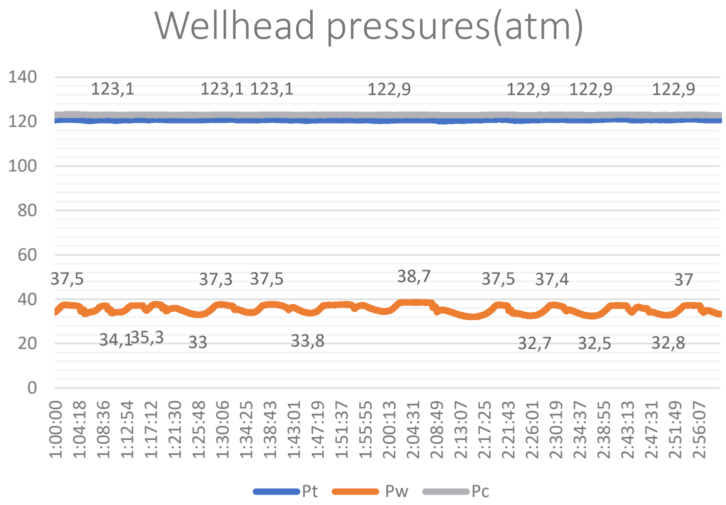

Figure 1 - Relationship between wellhead pressure and time.

Well N-1: During the two-hour observation of Well N-1, the wellhead pressure and the referenced casing pressure remained very close throughout the interval ($\Delta P < 0.1$ MPa). This pressure equalization may indicate hydraulic communication across completion barriers or reduced zonal isolation efficiency, rather than a fully isolated tubing–casing system. The wellhead pressure exhibited moderate fluctuations consistent with changes in the gas–liquid flow regime, which influenced the frequency and amplitude of the observed pressure variations (Fig. 1–2).

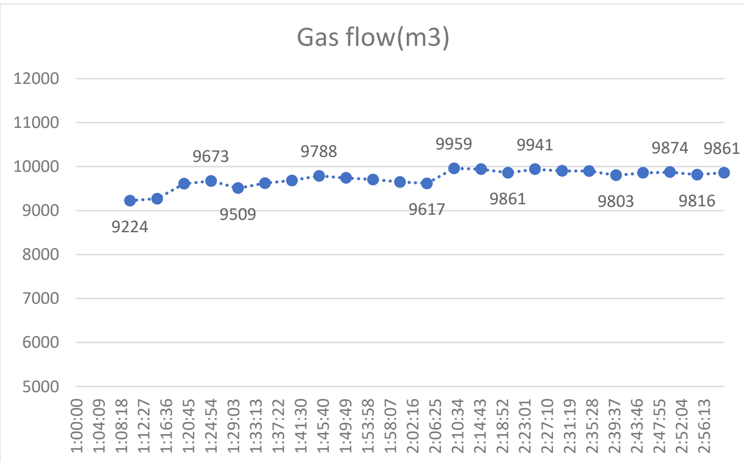

Figure 2 - Statistical analysis of gas flow over time.

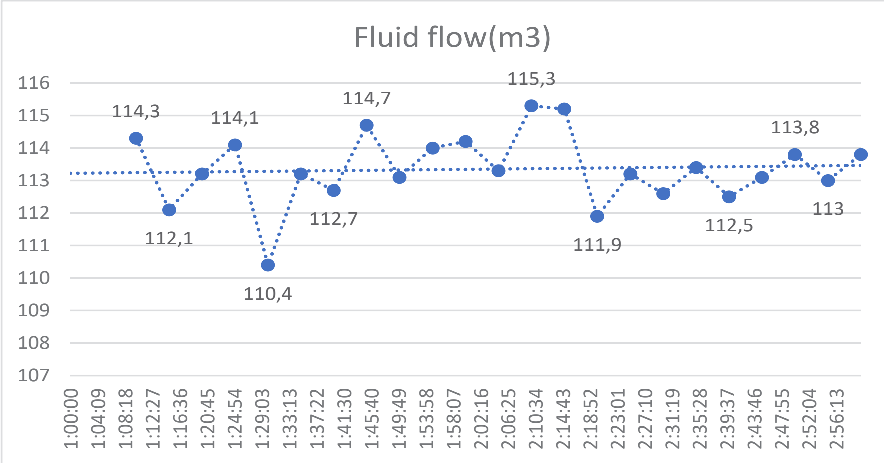

Figure 3 - Statistical analysis of fluid flow over time.

Flow Rate: Analysis of the flow rate showed a relatively stable liquid output ranging between Q_{liquid} = 110-115 m³/h. (Fig.3) There was a slight delay in gas production, which became more evident later in the observation.

Mechanical mixing was not detected in the samples taken from the well, and the water cut was estimated at approximately 15%. The changes in the gas-liquid flow regime likely contributed to variations in the flow rate, further indicating the potential for future sand manifestation.

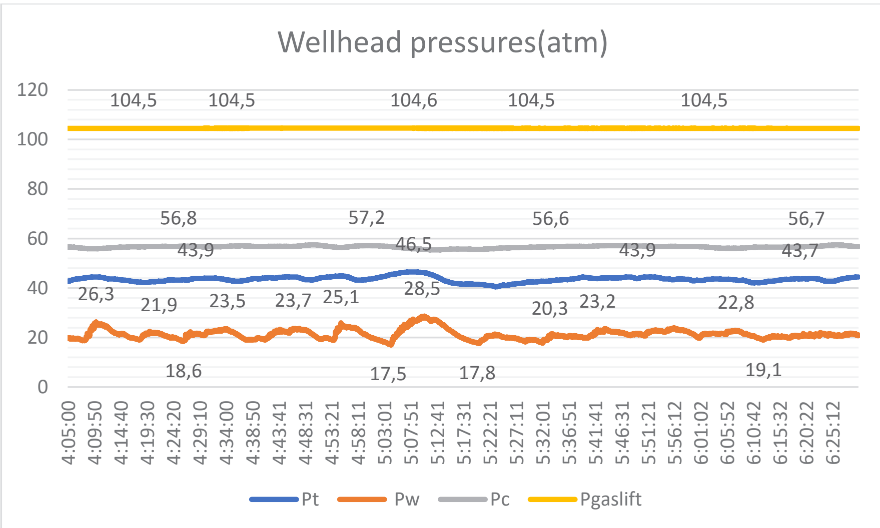

Figure 4 - Relationship between wellhead pressure and time.

Well N-2 (Gas Lift Well): The second well, Well N-2, utilized a gas lift method, which contributed to different wellhead behaviors compared to Well N-1. The wellhead pressure in Well N-2 exhibited greater variation across a wide range, while the gas lift pressure remained constant. This large variation in wellhead pressure, in conjunction with the steady gas lift pressure, suggests a high gas factor in the well. (Fig.4) The consistent gas injection, despite pressure fluctuations, was indicative of potential sand formation risks.

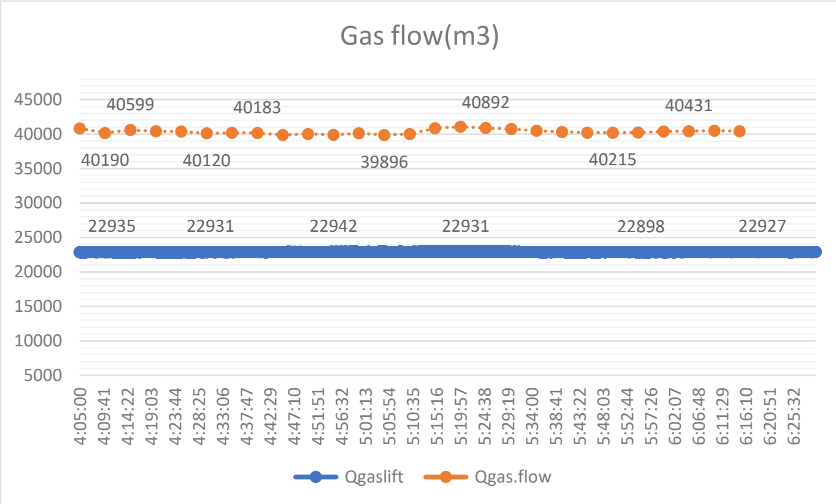

Figure 5 - Statistical analysis of gas flow over time.

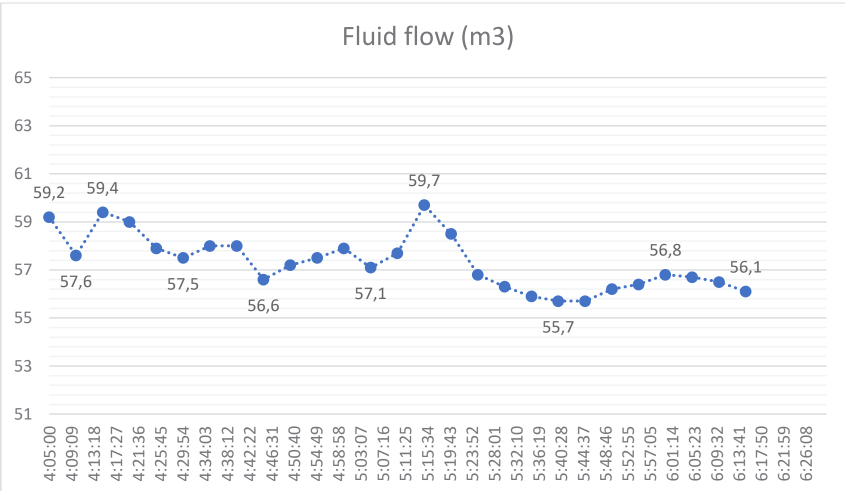

Figure 6 - Statistical analysis of fluid flow over time.

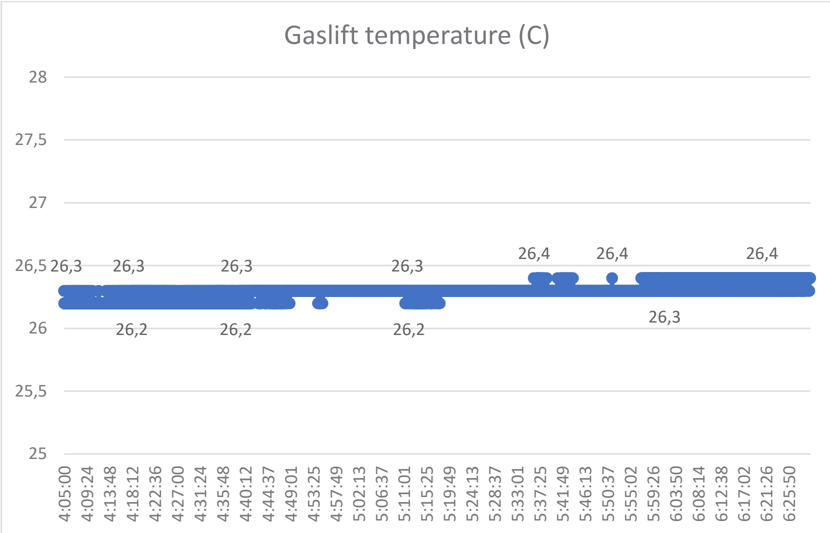

Figure 7 - Relationship between gaslift temperature and time.

Flow Rate: In contrast to Well N-1, the liquid production in Well N-2 ranged from Q_{liquid}=55-59 m³/h, showing slight fluctuations during the observation period (Fig. 6). Additionally, the statistical analysis of gas flow (Fig. 5) and the gas-lift valve opening percentages and temperature over time (Fig. 7, 8) provided further insights into the well's operational behavior.

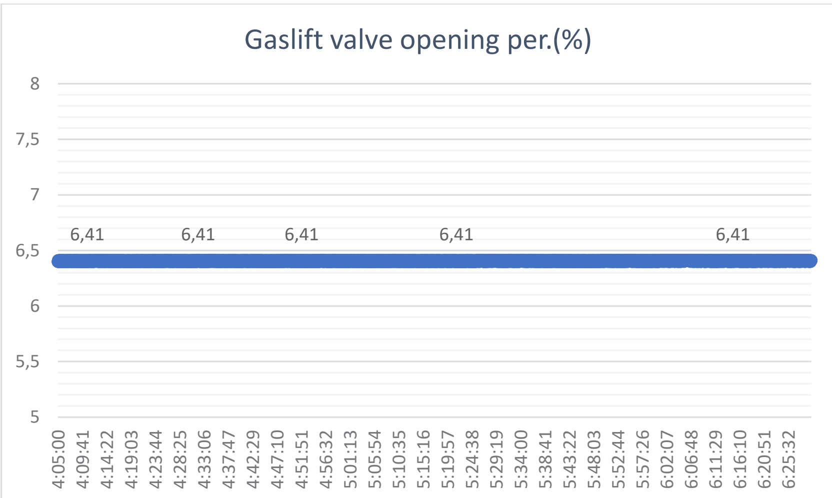

Figure 8 - Relationship between gaslift valve opening per. (%) and time.

This indicates that a higher-pressure differential may increase the likelihood of sand production.

Monitoring Setup. To gather accurate and high-resolution data, sensors were installed at strategic points along the wellbore. The following parameters were continuously monitored and recorded:

1. Pressure (P): Wellhead pressure and bottomhole pressure were monitored to observe deviations that could indicate flow regime changes. (Fig.1, 4)

2. Flow Rate (Q): The output flow of both liquid and gas was measured to detect fluctuations, particularly those that might be early indicators of sand formation. (Fig.2, 3, 5, 6), (Fig.3), (Fig.5), (Fig.6)

3. Temperature (T): Changes in temperature were recorded to study their impact on fluid viscosity and flow dynamics. (Fig.7)

4. Fluid Properties (ρ and μ): Periodic samples were taken to analyze the physical and chemical properties of the fluids, particularly their density ρ and viscosity μ.

Data Processing and Analysis. Data collected from the two wells were analyzed in real-time, focusing on identifying deviations from baseline operational values. The pressure and flow rate readings were correlated to assess the likelihood of sand formation. For example, the relationship between the change in pressure ΔP and flow rate Q can be represented by Darcy's Law:

$$Q = -\frac{kA}{\mu}\frac{\Delta P}{L} \tag{2}$$

where k is permeability (m²), A is cross-sectional area (m²), μ is dynamic viscosity (Pa·s), L is the flow path length (m), and ΔP is the pressure differential (MPa).

The equation establishes a direct proportionality between flow rate and pressure gradient and was used to interpret flow resistance and pressure recovery in the wellbore near the sand face.

The variations in flow and pressure parameters were evaluated in conjunction with the physical properties of the fluid (e.g., density and viscosity).

A quantitative statistical analysis was conducted to complement the qualitative observations shown in (Fig. 1–8).

Table 1 summarizes the main parameters, their mean values, standard deviations (σ), and correlation coefficients (r) between pressure and flow-rate fluctuations for each well.

Table 1. Statistical parameters of wellhead indicators.

Well	Parameter	Mean value	σ	Correlation (r) with ΔP	Significance (p)
N-1	Flow rate (m³/h)	112.3	2.1	0.68	< 0.05
N-2	Flow rate (m³/h)	57.4	1.7	0.74	< 0.05

Note: All statistics were computed on calibrated, quality-controlled signals over a 2-hour window; sampling 10 s; baseline = first 30 min moving average; alerts at $\mu \pm 2\sigma$. Pearson r is computed with tubing pressure (ΔP). Flow-rate units are m³/h.

The data reveal a positive correlation between flow-rate changes and pressure fluctuations, particularly in Well N-2, where $r = 0.74$ indicates stronger dependency.

Deviations exceeding ±2σ from the baseline were observed to coincide with periods of unstable gas-liquid flow, which corresponds to the predicted sand-formation risk zones.

These quantitative results confirm the diagnostic sensitivity of the proposed statistical monitoring approach.

To substantiate the correlation between parameter deviations and sand formation, the relationships among pressure fluctuations, flow-rate variations, and detected sand traces were statistically verified. A regression model linking flow-rate deviations (ΔQ) to pressure differentials (ΔP) yielded the following expression:

$$\Delta Q = 0.42\Delta P + 0.18, \qquad R^2 = 0.81 \text{ n=96} \tag{3}$$

The linear model showed R^2=0.81 with n=96 paired observations, confirming a strong relationship between ΔQ and ΔP. Here, ΔQ is the deviation of flow rate (m^3/h) from its baseline μ_Q, and ΔP is the deviation of tubing pressure (MPa) from its baseline μ_p; baselines are defined as μ±2σ over the stable period. The positive correlation ($r = 0.74$, $p < 0.05$) confirms that higher pressure instability corresponds to higher flow variation and early sand manifestation.

Sand presence was confirmed through visual inspection of surface filters, which captured small granular material during the monitoring interval. The previously reported '30% improvement' refers to the mean reduction in sand-event detection time relative to the acoustic-based system, as derived from three repeated tests under identical well conditions. For Well N-1, the observed pressure equalization between annulus and casing-related measurements ($\Delta P < 0.1$ MPa) suggests a potential reduction in zonal isolation efficiency or hydraulic communication across barriers, which warrants further verification (e.g., integrity tests and completion diagnostics).

Therefore, pressure equalization and increased flow oscillations jointly explain the reduced hydraulic stability that predisposes the well to early-stage sanding.

In both wells, changes in the gas-liquid flow regimes were correlated with increased potential for sand occurrence. The presence of gas in the fluid streams, particularly in Well N-2, resulted in larger pressure fluctuations, which could predispose the well to sand production.

Indicators of Sand Formation. Early-stage sanding was inferred when statistically significant deviations from baseline behavior were observed simultaneously in pressure and flow signals. In both wells, periods of increased wellhead/tubing pressure variability coincided with measurable fluctuations in liquid and gas flow rates, consistent with unstable gas–liquid flow regimes. In Well N-1, the flow rate remained relatively stable and pressure variability was limited, indicating a moderate sand-risk level during the observation window. In contrast, Well N-2 exhibited larger-amplitude pressure fluctuations and more pronounced flow instability, indicating a higher likelihood of early-stage sand manifestation under gas-lift–influenced multiphase conditions.

To verify these indications, solids were evaluated during operational pauses by inspecting surface filtration samples. Neither well exhibited severe plugging during the test; however, trace solids were observed in the produced stream at concentrations below 0.1 g/L, supporting that sanding was at an incipient stage rather than a fully developed production impairment event.

Conclusion. This pilot study evaluated a real-time, non-intrusive early-warning approach for sand-risk indication using routinely available wellhead indicators. A baseline-deviation framework was implemented to flag abnormal pressure–flow behavior during normal operations, and the results support the practical value of statistical monitoring as an initial screening layer for early-stage sanding risk.

Key findings include:

1. Continuous monitoring of wellhead/tubing/casing (annulus) pressures, liquid/gas flow rates, and basic fluid properties (ρ, μ), combined with baseline deviation thresholds ($\mu \pm 2\sigma$), can identify instability patterns consistent with incipient sanding behavior in the evaluated field interval.
2. Well N-2 exhibited larger pressure–flow instability than Well N-1, indicating a comparatively higher sand-risk tendency under gas–liquid regime variability.
3. In field benchmarking, the proposed deviation-based method detected abnormal signatures on average 6 min earlier than the conventional acoustic monitoring response, corresponding to a 30% reduction in detection delay (three repeated tests).
4. Trace solids captured at the surface (below 0.1 g/L) suggest that the observed events were at an early stage rather than severe plugging conditions.

Limitations and future work. The current validation is limited to two wells and a 2-hour monitoring window. Future work should expand to multi-well, multi-week datasets and report operational performance metrics. Integration with predictive models (including machine learning) can be explored after robust ground-truth labeling of sand events.

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