processes

MDPI

Article

Application and Analysis of Array Production Logging Technology for Multiphase Flow in Horizontal Wells

Renwei Luo [1,†], Jianli Liu [2,†], Dong Yang [1,3,*] and Qiao Deng [1,3,*]

[1] Hubei Key Laboratory of Oil and Gas Drilling and Production Engineering, Yangtze University, Wuhan 430100, China; sevrusluo1115@163.com
[2] School of Mechanical Engineering, Yangtze University, Jingzhou 434023, China; 201972315@yangtzeu.edu.cn
[3] School of Petroleum Engineering, Yangtze University, Wuhan 430100, China
* Correspondence: dengqiao@yangtzeu.edu.cn (Q.D.); 521005@yangtzeu.edu.cn (D.Y.)
† These authors contributed equally to this work.

Abstract: Production logging (PL) instruments play a pivotal role in the comprehensive management and monitoring of oil and gas reservoirs. These devices facilitate the resolution of complex flow diagnosis challenges throughout the life cycle of hydrocarbon field exploitation. However, the advent of highly deviated well drilling technology has exposed certain limitations inherent in conventional centralized logging sensing techniques. When fluid flow within horizontal wells becomes segregated or even laminar, these traditional methods struggle to accurately decipher the zonal productions of oil, gas, and water. To address this challenge, multi-array production logging tools were developed in the late 1990s. Historically, these tools were characterized by considerable lengths, reaching up to 30 feet for an entire suite incorporating flow speed and holdup sensors that were not always collocated. Despite the integration of multiple sensors, uncertainties in determining flow profiles persisted. In this paper, we propose a novel integrated multi-parameter evaluation method based on measurements from a recently developed ultracompact flow array sensing tool, aimed at enhancing the accuracy of reservoir evaluation. The validity of the multi-parameter method is substantiated through a comparison of the new tool with an industry benchmark array PL tool on the same well. By combining the monitoring results, an optimization strategy for oil and gas extraction is presented, which is expected to improve the oil and gas recovery rate, thereby providing guidance for subsequent extraction endeavors. Moreover, we demonstrate how this innovative integrated workflow significantly enhances energy savings and efficiency, further underlining its value in modern oil and gas field management.

Keywords: production logging; production monitoring; array logging; horizontal well logging; production profiling

Citation: Luo, R.; Liu, J.; Yang, D.; Deng, Q. Application and Analysis of Array Production Logging Technology for Multiphase Flow in Horizontal Wells. *Processes* **2023**, *11*, 3421. https://doi.org/10.3390/pr11123421

Academic Editors: Zhan Meng, Qingbang Meng and Bin Liang

Received: 18 November 2023
Revised: 4 December 2023
Accepted: 8 December 2023
Published: 13 December 2023

1. Introduction

Production logging refers to an array of monitoring procedures in oilfields for assessing multi-phase fluid systems, including oil–water, oil–gas, or oil–gas–water [1,2]. These procedures involve utilizing various measurement devices to track the status of fluids both within and outside the well throughout its lifespan. The primary objective of these procedures is to continuously monitor and evaluate the distribution of fluids in the well and ensure the structural integrity of the well, enabling the accurate diagnosis of reservoir productivity and informed decision-making regarding the control of unwanted fluids like produced water [3–10].

During production logging, specialized logging equipment is inserted directly into the well and maneuvered downward to gather data on various parameters within the well. This information provides insight into the properties of incoming or outgoing fluids and their flow patterns in each formation, serving as the foundation for creating fluid flow profiles [11,12].

During the progression of unconventional oil and gas wells, the utilization of horizontal well exploitation technology has gained widespread acceptance and application. As a result, horizontal wells have evolved into a pivotal technique for achieving consistently high and steady outputs. However, traditional testing modalities are incapable of delivering logging instruments to the base of horizontal wells, with some instances even resulting in upward buckling. The gravitational forces exerted by fluids lead to the occurrence of fluid separation in horizontal wells, characterized by a stratified flow dominated by gas, oil, and water descending from top to bottom. This significantly diverges from the manner in which fluid separation manifests in vertical wells.

Despite the successful demonstration of fluid profile visualization via conventional logging tools in vertical wellbores, addressing the issue of phase separation [13], there are certain limitations in high-gradient or horizontal wells. Specifically, the upper portion tends to contain lighter phases [14], while the lower regions harbor heavier phases, particularly at the base of horizontal wellbores, where sedimentation phenomena can potentially occur. Such occurrences pose constraints on the regular operation of measuring equipment, leading to acquired data that fail to provide an accurate representation of the flow attributes of horizontal wells [15]. In response to this scenario, a novel transmission methodology has been put forth, entailing the deployment of advanced logging instrumentation to the base of horizontal wells, complemented by sophisticated data interpretation methodologies. This innovative approach carries considerable implications for the advancement of production logging in horizontal wells [16].

Currently, two predominant strategies prevail for transporting logging instruments to targeted depths within horizontal sections: crawler transportation and continuous tubing transport. Crawler transportation boasts several technical advantages, including ease of operation, real-time data collection capabilities, and cost-effective logging expenses. However, this method may present issues related to insufficient power when towing logging tools over extended horizontal well sections. Moreover, crawler conveyance necessitates a high degree of wellbore wall smoothness and well fluid cleanliness, introducing potential impediments and the possibility of blockages or jams [17]. On the contrary, continuous tubing operations offer distinct benefits, including the capacity to dislodge sand, blockage debris, and other hindrances from the wellbore. Additionally, continuous tubing can transmit substantial quantities of power and accommodate longer distances. Hence, the majority of horizontal well operations opt for continuous tubing as the preferred mode of delivery for logging instruments [18,19].

The advent and implementation of array logging tools have significantly ameliorated the limitations associated with conventional logging technologies [20]. This innovation represents a paradigm shift in addressing the challenges of detecting phase separation caused by variations in fluid density within horizontal or inclined wells [10]. The introduction of array logging holds considerable implications and value across all stages of oil and gas field exploration, development, and production. Array logging constitutes an extensive measurement strategy employing an ensemble of multiple sensing elements embedded within a set of measurement probes to yield additional information about formation parameters, refine the characterization of formation types, and facilitate the real-time monitoring of subsurface dynamics. This method significantly enhances the precision of logging data, fostering substantial advancements in the description and management of oil and gas reservoirs.

The application of array logging technology in horizontal or inclined wells has been extensively studied, with a notable breakthrough being the utilization of conductivity probe arrays to measure three key parameters: water level, water phase conductivity, and sensor orientation [2]. This method enhances the range of water level estimation while improving accuracy and reliability. To address dynamic monitoring of oil fields during periods of high water content, an array probe output profile recorder was developed to improve logging success and minimize measurement errors [21]. Furthermore, the principles of the MAPS array imaging instrument were expanded upon [16], along with the mechanisms involved in deploying production logging in horizontal wells, including the Capacitor Array Tool (CAT), Resistive Array Tool (RAT), and Spinner Array Tool (SAT) components, as shown in Figure 1. The feasibility of implementing a continuous tubing transport array tool in shale gas wells was confirmed after a field evaluation [18], providing evidence for the robustness of data interpretation methods and emphasizing the centrality of production logging.

Figure 1. MAPS logging instruments. Adapted from [3].

In-depth studies utilizing the MAPS array production logging instrument in unconventional shale formations highlight the benefits of this technology in high-gradient environments [13]. The combination of the Multi-Array Production Suite (MAPS) and Digital Noise Tool (DNT) for downhole production logging produced best practices for assay results [22]. Additionally, a model based on a nonlinear optimization algorithm was developed to interpret natural gas production profiles recorded using MAPS arrays, highlighting the strong connection between formation fracture pressure and gas production capacity [15]. The Fluid Scanning Imaging (FSI) technology's working principle was understood and applied to three-phase flow wells with excellent measurement results [23]. FSI production profile logging in shale gas horizontal wells promotes progress in trajectory optimization, segmental fracturing parameter optimization, and production management [24]. In addition, the algorithms of a dedicated FSI array imaging instrument were facilitated by the integration of rotators and probes to generate multiphase water-holding profiles [25]. FSI yield logging accurately reflects the water-holding rate and gas content of each fracturing phase, effectively evaluating the fracturing effect and meeting the needs of shale gas wells [26].

Despite these promising developments in horizontal well measurements, certain pressing issues remain unsolved. Instrument size remains excessive, limiting instruments' ease of navigation to well bottoms and increasing their susceptibility to missing critical measurement points. Turbine flowmeters struggle to function adequately in thick-oil environments. Moreover, calculations are complex, necessitating the simultaneous use of resistance and capacitance rate sensors for determining the three-phase holding rates of oil, gas, and water [1]. With these considerations in mind, this study proposes a cutting-edge integrative assessment approach rooted in flow array sensing technology to gauge the comprehensive dynamics of oil and gas wells. Further validation ensues through the comparison and examination of FSI and FAST measurements in identical oil and gas wells, culminating in the formulation of an optimized extraction strategy to bolster extraction efficiencies.

The following describes the structure of this paper: Section 2 will introduce the measurement parameters of FAST and FSI; Section 3 will show the monitoring results of FAST and FSI and compare the yield analyses of the two methods; Section 4 will discuss the consistency and differences between the monitoring tools of FAST and FSI; and finally, Section 5 will summarize the paper.

2. Materials and Methods

2.1. Example of Well A and Actual Measurement Method

Well A featured profound engineering complexities, reflected by its depth of −5368 m and horizontal section length of −1935 m. To optimize oil recovery, a strategic approach was implemented involving meticulous segmentation of the entire well into 21 subsections, each subjected to hydraulic sand fracturing technology. Hydraulic sand fracturing utilizes pressurized fluids, predominantly laden with sand, to perforate rock layers, forming cracks conducive to the passage of oil and gas.

Subsequently, Well A exhibited impressive and consistent performance, generating nearly 100,000 cubic feet of natural gas daily. These production figures closely align with initial projections, indicating that the selected strategies and methodologies yielded tangible dividends.

The experimental procedures encompass four principal stages:

1. Employing the FSI logging instrument to conduct single-pass, bi-directional testing along the trajectory of borehole A at velocities of 6 m/min and 12 m/min, respectively, and recording and analyzing the monitoring statistics for each trial run.
2. Leveraging the FAST logging instrument to execute single-pass, bidirectional testing along the trajectory of Borehole A at speeds of 5 m/min and 10 m/min, respectively, while capturing and analyzing the corresponding monitoring data.
3. Establishing a stratigraphic model for Well A based on compiled data from FSI, FAST, and additional logs and integrating various interpretation and analytical software (Emeraude 5.40) to perform exhaustive parsing of logging data to glean highly precise subsurface geological information and reservoir distribution patterns, enabling informed decision-making in subsequent oil recovery planning.
4. Providing an elaborate and meticulous account of the data acquisition, processing, and interpretation processes in conjunction with the assembled stratigraphic model and geological information. The report should detail the physical attributes of the well, geological characteristics, and potential reservoir insights. Concurrently, the review and forecasting results aim to effectively inform drilling and production operations.

2.2. FSI and FAST Monitoring of Key Parameters

Fluid Scanning Imaging (FSI) is an adaptable logging tool devised to accommodate high-inclination and horizontal well settings. It features an innovative assembly of three sensor arrays housed within retractable arms, comprising 5 rotators, 6 optical probes, and 6 electrical probes, respectively (Figure 2). Five rotators are mounted onto one arm and serve to scientifically quantify the velocity profile of downhole fluids, detecting any abrupt variations or abnormalities. The exceptional precision of these rotators enhances measurement accuracy and reproducibility, which is instrumental in illuminating fluid dynamics within the reservoir. Six electrical probes and six optical probes, situated on a separate arm, facilitate real-time monitoring of the water and gas saturation levels of the formation. These probes leverage state-of-the-art physical concepts and sophisticated manufacturing techniques to render accurate and prompt assessments of water and gas contents. Significantly, the controllable deployment of the telescopic arms enables the optimal recording of holding rates and fluid velocity profiles across the vertical axis of the borehole cross-section [23], presenting an intuitive and dependable configuration for acquiring precise measurements.

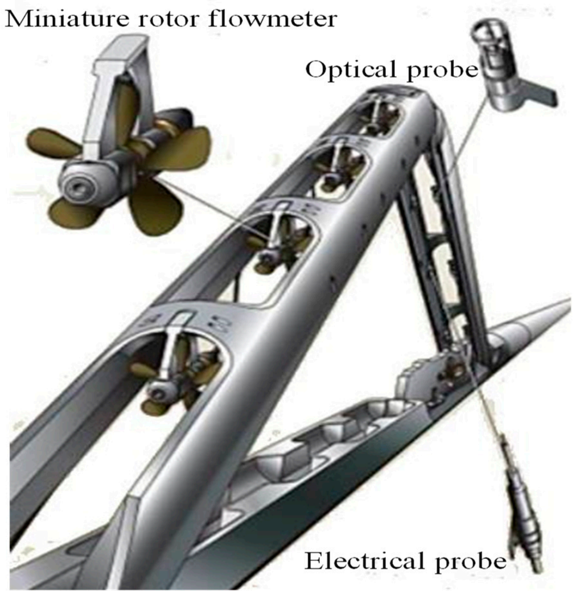

Figure 2. FSI logging instruments. Adapted from [27].

FAST represents a highly modular, compact multi-phase flow metering device offering customizable configurations with significantly reduced dimensions compared to conventional logging assemblies, rendering it feasible to capture readings from a single spatial point. Its 4-arm, robust bow-mounted corrector affixed to the outer diameter shaft permits accurate assessments via two condition-monitoring sensors attached to each arm for eight distinct nodes (Figure 3), further enhanced by adjustable probe head lengths for uninterrupted exploration across varied zones within the wellbore. Additionally, a high-resolution pressure sensor, a rapid-response temperature sensor, and inclination/azimuth sensors are incorporated into its core segment [28].

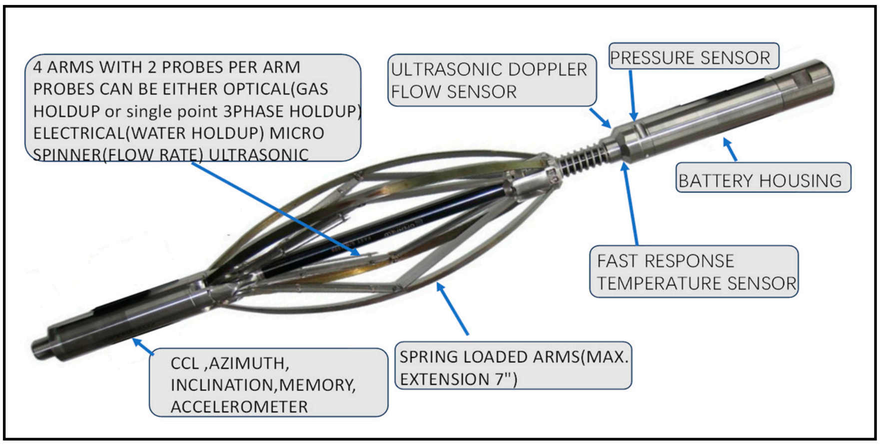

Figure 3. Flow array sensing tool.

FAST encompasses diverse sensor arrays, including optical, electrical, and acoustic modalities, delivering a wide spectrum of logging data to facilitate a nuanced examination of multi-phase flow patterns in oil wells. Its integrated, high-fidelity, high-throughput sensors equip it to execute multifaceted, high-accuracy assessments, exemplified by real-time tracking of pressure and temperature fluctuations in well walls and fluids and geosteering for logging operations, enhancing the comprehension of well trajectories and reservoir orientation.

Adaptive algorithms and cutting-edge computation models in the data analysis phase allow for the comprehensive integration of logged data, unlocking a deeper comprehension of reservoir geology and fluid behaviors. Thus, FAST instrumentation effectively streamlines the appraisal of oilfield production capacities and reservoir development characteristics, significantly bolstering scientific rigor and accuracy in extraction decisions.

The electrical probe employed in the FAST logging instrument relies upon multi-electrode theory, aimed to assess the impedance of surrounding fluids utilizing an electric probe. Capitalizing on the inherent resistance properties of oil and gas, it serves as a discerning tool for distinguishing between water and hydrocarbon volumes. The design channels current density towards the probe's tip, significantly reducing the volume under scrutiny relative to traditional probes. Water saturation levels are gauged by computing the proportion of time spent in contact with water versus the total sampling duration.

When encountering unbroken hydrocarbon mediums, real-time water-holding rate computations leverage data points exceeding pre-determined thresholds. Conversely, upon entering contiguous water bodies, the inversely proportional decline in water-holding rates corresponds to data points falling below said dynamic threshold [28]. As depicted in Figure 4, the probe measures liquid conductivity at intervals of several tens of microseconds, generating a binary electrical signature differing starkly between water and hydrocarbons. By establishing a cut-off demarcating water from hydrocarbon, the mechanism functions as a miniaturized, quick-response conductivity gauge, imparting improved measurement reliability and fidelity [29].

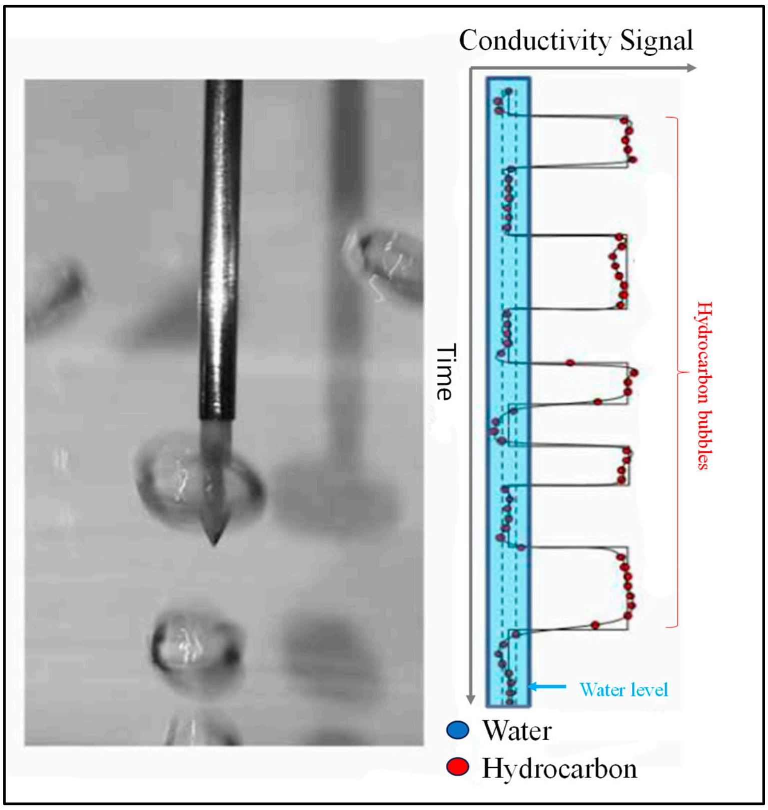

Figure 4. Electrical probes and conductivity waveforms are used for detecting gases in liquids. The blue bubbles in the graph indicate the aqueous phase, and the red bubbles indicate the hydrocarbon phase. Setting the appropriate thresholds can distinguish the aqueous phase from the hydrocarbon phase. Adapted from [28].

Optical probe technologies have spawned a novel breed of fluid recognition schemes deviating from traditional optically based bubble detection methodologies [30], featuring an exclusive biconical architecture leveraging sensitivity towards optical fluid indices. Reflective indexes across diverse fluid species fall within a finite range, where gaseous substances exhibit values near unity, waters average around 1.35, and crude oils approximate closer to 1.5. Optical probe designs spanning the complete scope of reflective index variability, ranging from 1.0 to 1.6, offer substantial benefits over conventional techniques.

Fast-paced refractive index measurements captured at periodic intervals of tens of microseconds endow optical probes with swift detection capabilities. Moreover, since oil and water exhibit comparable fluid properties, optical probes prove advantageous in differentiating gases from liquids. Complementary combinations of electrical and optical probes enable the simultaneous determination of triphasic retention rates for oil, water, and gas at solitary locations [31], as visually demonstrated in Figure 5.

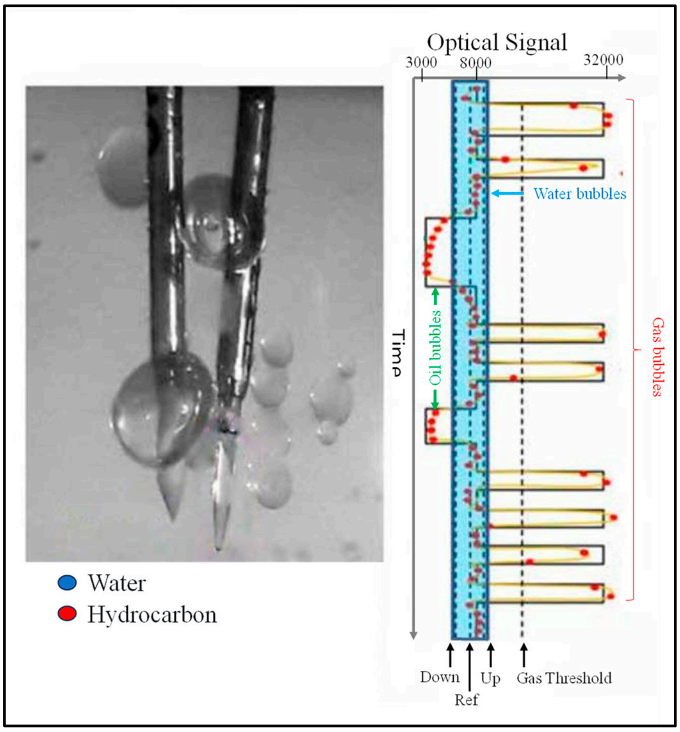

Figure 5. Blue indicates the water phase, and red indicates the hydrocarbon phase. Optical probes are based on electrical probes with appropriate thresholds set to distinguish between oil and gas phases. Adapted from [28].

Ultrasonic Doppler flowmeters draw upon the Doppler effect, describing the frequency differential between signals transmitted and echoed off a moving object, serving as a function dependent on said motion [31]. In fluid flow-rate estimations, ultrasound emittance from transducers paired with the backscattered signals during fluid passage generates a frequency shift directly proportional to the scatterer's relative velocity to the transmitter–receiver pair, thereby enabling the calculation of volumetric flow rate by integration [32].

Significantly, the frequency deviations emanating from the ultrasonic array demonstrate a pronounced correspondence with rotational velocity from the microrotary mechanism, potentially substituting the latter in mitigating blockages due to wax buildup, scaling, asphaltene precipitation, sediment deposition, heavy oil formation, etc. Moreover, for sloped and horizontally oriented wells, multiplexed sensors represent compelling information sources in concurrent assessments, facilitating the utilization of probabilistic production well testing interpretations. From this vantage point, comprehensive visualizations of downhole flows may be reconstructed [31].

3. Results

3.1. Comparison of Testing Phenomena in Well A

Figures 6 and 7 show the conditions of the FSI and FAST technologies, respectively, after the completion of the production profile test and well exit. It can be observed from the figures that both the FSI and FAST tools have sludge and debris adherence phenomena during the actual operation. Since the FSI tool is designed with grooves, it is easier for the main part of the tool to accumulate a large amount of sludge, which may negatively affect the normal operation of the rotator if too much sludge accumulates during the measurement.

Figure 6. Actual FSI instrument out-of-well site.

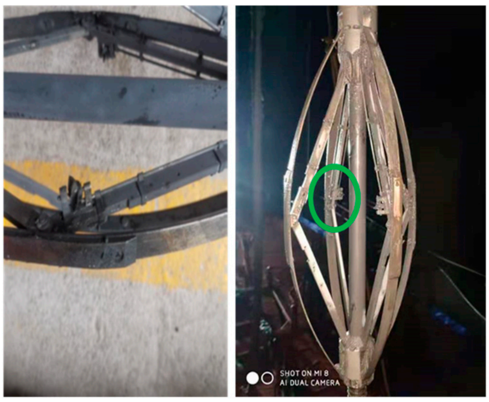

Figure 7. Actual FAST instrument out-of-well site.

By analyzing the labeling of Figures 6 and 7, we can observe that the rotator on the FSI extension arm is obscured by both sides of the groove, whereas the contrasting FAST technology is only obscured by one side of the support arm. Such a design ensures that the FAST rotator is able to make contact with a larger area of the measured object, thus potentially providing higher measurement accuracy. Table 1 details a comparative analysis of the performance of the FSI and FAST technologies in terms of the relevant parameters during out-of-well operation.

Table 1. Basic parameters of the model.

	FSI Out-of-Well Status	FAST Out-of-Well Status
Measuring device	Two rotors failed to rotate (mud deposits)	Structural integrity
Measurement is blocked	Not yet at the bottom of the well (100 m from FAST)	All rotors maintained normal function
Measuring time	Base repair: 2 days to complete the logging	Two well surveys in 50 h
Measuring depth	The effective data depth of the final measurement was 4600 m	The final effective data depth was 4700 m

3.2. Data Quality Analysis

Figure 8 presents exhaustive depictions highlighting the variation in flow patterns during the logging processes conducted using the FSI and FAST devices. During reciprocal logging tasks, the FSI instrumentation showcased inconsistencies in the quality and repeatability of rotor-derived information throughout sections 3–8 (down to 4600 m) alongside suboptimal data collection from probes 1, 3, and 4, affecting the veracity of the water-holding probes' output. However, FAST instruments registered standard rotatory data within the uppermost sections (3–7 (extending beyond 4700 m)), indicating environmental resilience, as well as superior-quality data collected across the subsequent segments (8–21).

Upon consolidating the logging outcomes, the output profiles illustrated in Figure 9 indicate that FAST devices effectively capture productivity contributions, segmented as 21-8, while acknowledging a holistic assessment of outputs generated from 7-1. On the contrary, FSI equipment divides well performance into contributions originating from sections 21-9, but aggregates output contributions from segments 8-1. Notably, the augmented number of data points gathered by FAST renders it conducive to capturing supplementary metrics in essential regions, particularly since FSI equipment experiences limitations due to prolonged string lengths preventing access to the lowermost portions of the well.

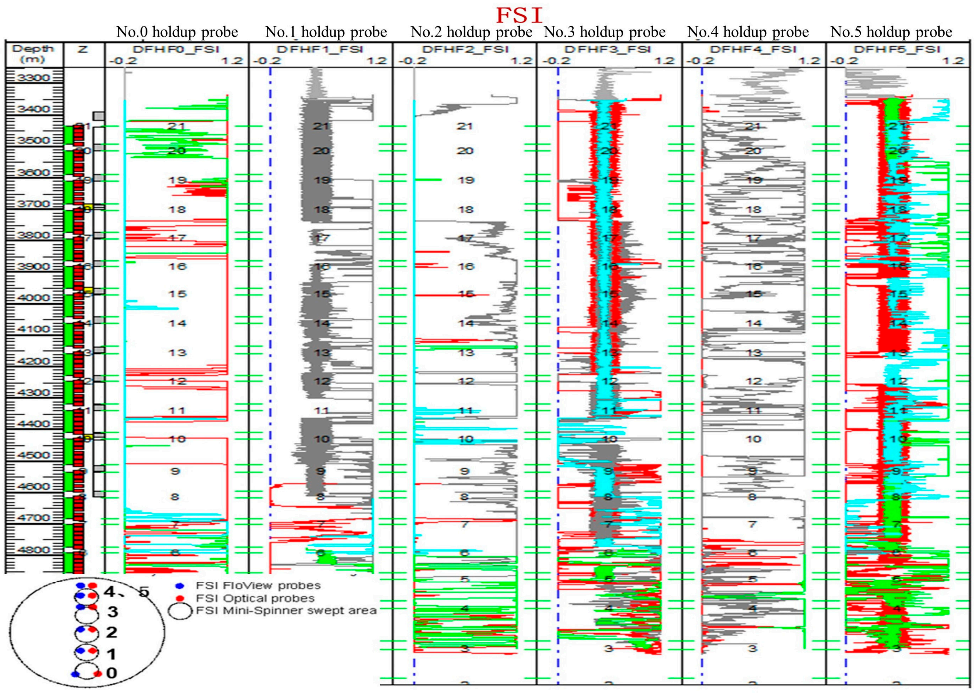

Figure 8. *Cont.*

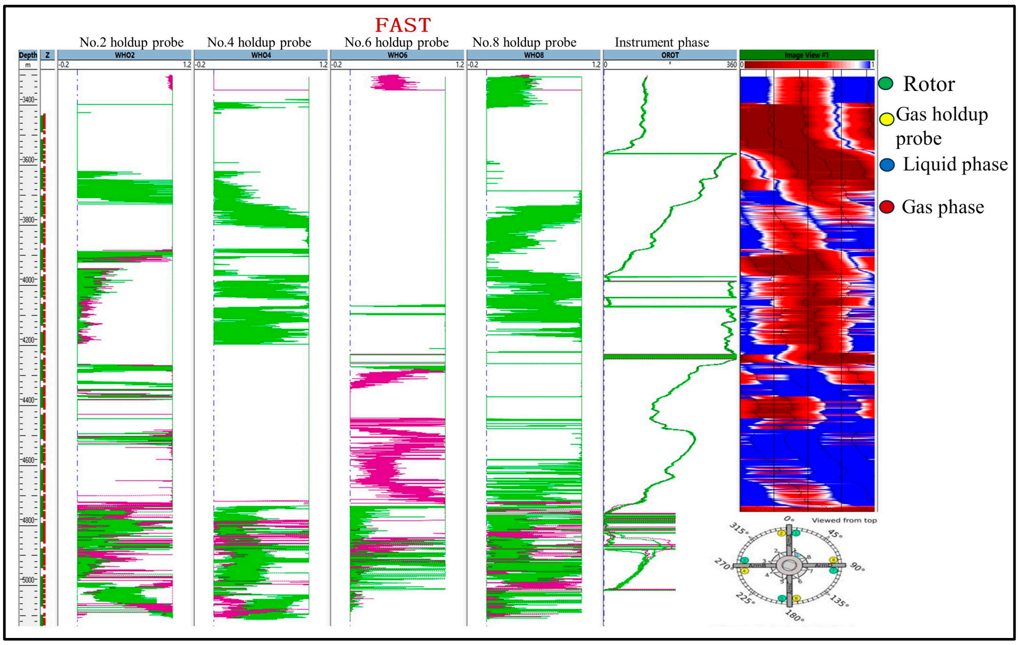

Figure 8. Response of FSI and FAST to flow state change. Poor repeatability of FSI up- and down-gauge water-holding rate probe data (effects of flow regime changes); individual probe anomalies (Nos. 1, 3, and 4); all FAST probes working properly; average repeatability of up- and down-gauge fiber-optic phase-holding rate probe data (effects of flow regime changes).

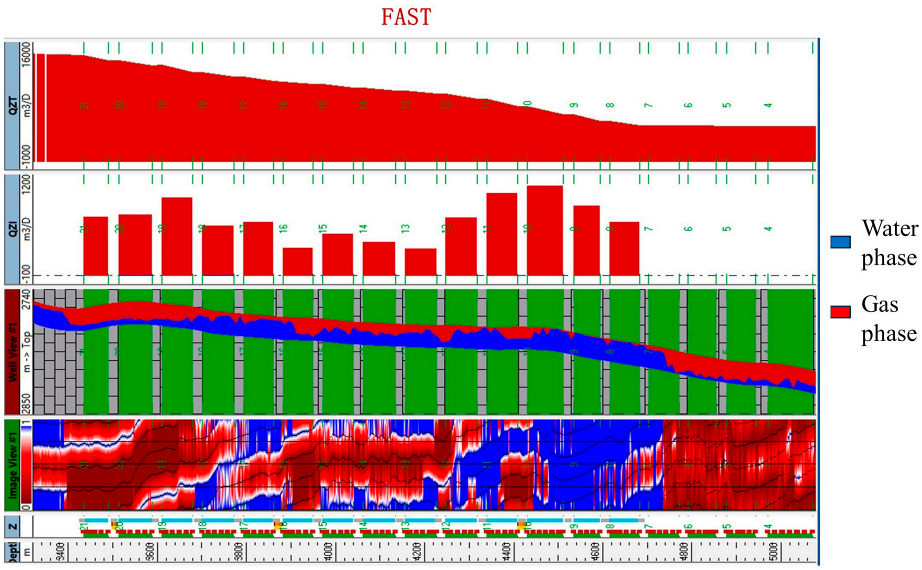

Figure 9. *Cont.*

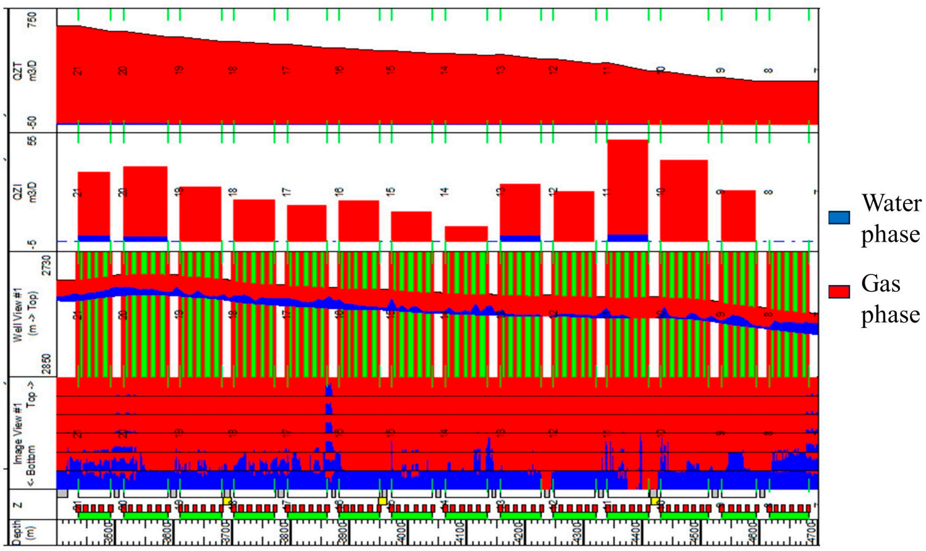

Figure 9. The production profile of FAST and FSI logging. FAST interpreted the segment 21-8 outputs, and segments 7-1 as a whole; FSI interpreted the segment 21-9 outputs, and segments 8-1 as a whole. FAST measured one more segment of key data than FSI.

4. Discussion

4.1. Consistency Analysis of FAST and FSI Test Results

The array logging tool is a diagnostic tool used to find the sweet spot. When the conventional seven-parameter logging method cannot meet the stratified flow pattern in deviated or horizontal wells, array logging tools can be used instead, so the FAST and FSI array logging methods can better capture the flow pattern among oil, gas, and water in horizontal wells. In the production profile in Figure 9, it can be seen which segments are the "sweet spots". In the early monitoring of open-hole wells, the 14th and 15th sections had reservoirs but relatively low production. To improve the recovery factor, water injection [33,34], acid injection [35–37], and secondary fracturing [38,39] can be used to increase the production of low-production parts.

The array logging tool serves as a diagnostic tool to locate water spots. In horizontal wells, due to the stratified flow pattern between oil, gas, and water phases, once the water outflow in the wellbore is relatively large, it will cause the whole wellbore to be plugged, and thus, the oil and gas in the deeper part of the wellbore will not be able to reflect the production. Array logging tools can find the water outflow point [40,41], which can be utilized to reduce water production and increase oil and gas production by using effective plugging methods.

4.2. Differential Analysis of FAST and FSI Assay Results

During the experimental testing of Well A, we employed two distinct measurement tools, FSI and FAST, to conduct a comprehensive analysis by comparing the data gathered from these devices. Despite the discrepancies observed in Figures 10 and 11, upon meticulous examination of the production profiling results for individual sections and clusters, it was discerned that these disparities were not substantial.

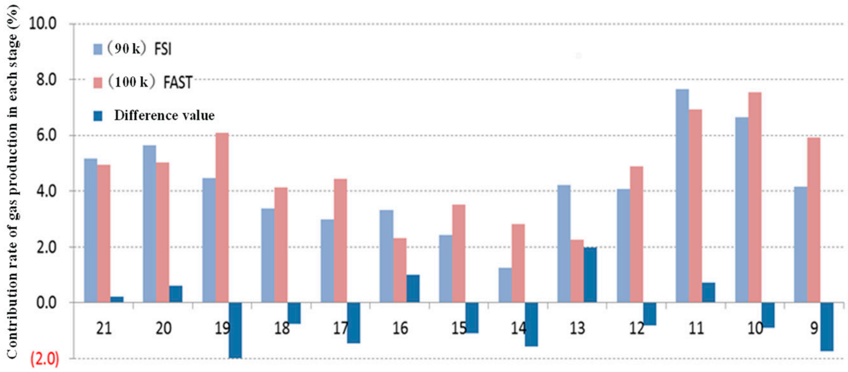

Figure 10. Comparison of production profile test results by segment analysis.

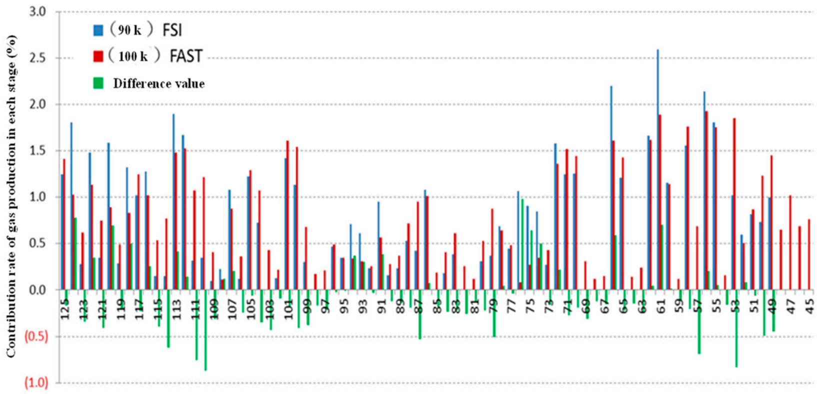

Figure 11. Comparison of production profile test results using per-cluster analysis.

The present analysis underscores that while minor variations exist between the two instruments' outcomes, such divergences may be amplified when undertaking a holistic assessment of yield tests involving simple segmentation vis à vis unit cluster configuration. Nevertheless, our overall scrutiny revealed that these biases remain within tolerable margins, thereby exerting minimal impact on the interpretation of the test findings as a whole.

In future endeavors, there is a pressing need to further explore and scrutinize these subtle differences to attain a more profound understanding of how instrumentation, measurement techniques, and data analysis can be optimized for enhanced performance in parturition testing.

In the context of FAST measurements, when pronounced fluctuations in the acquired data are detected, this instigates a response from Doppler sensors indicating a phase transition. This phenomenon is typically interpreted as indicative of the presence of multiphase fluids. The considerable signal alteration illustrated in Figure 12 implies that a phase shift occurred during this interval. At approximately 3400 m deep, the fluid within the wellbore transitions from a mixed gas–liquid phase to a pure gas phase; descending further to around 3600 m, the gas phase reverts back to a mixed gas–liquid phase. This occurrence underscores the exceptional capability of the FAST tool to provide robust data support for formation testing, even amidst perturbations such as sand outcrops encountered during the measurement process.

Both the FAST and FSI array logging tools are capable of monitoring production conditions in horizontal wells. However, the FSI tool solely relies on a rotator for fluid velocity detection. In unfavorable well conditions, such as sand or heavy oil, the rotator's functionality may be impaired, leading to decreased measurement accuracy. Conversely, the Doppler flow measurement method exploits acoustic waves to determine flow rates, enabling it to compensate for poor-quality rotor data or other obstacles by providing more accurate production profile test results.

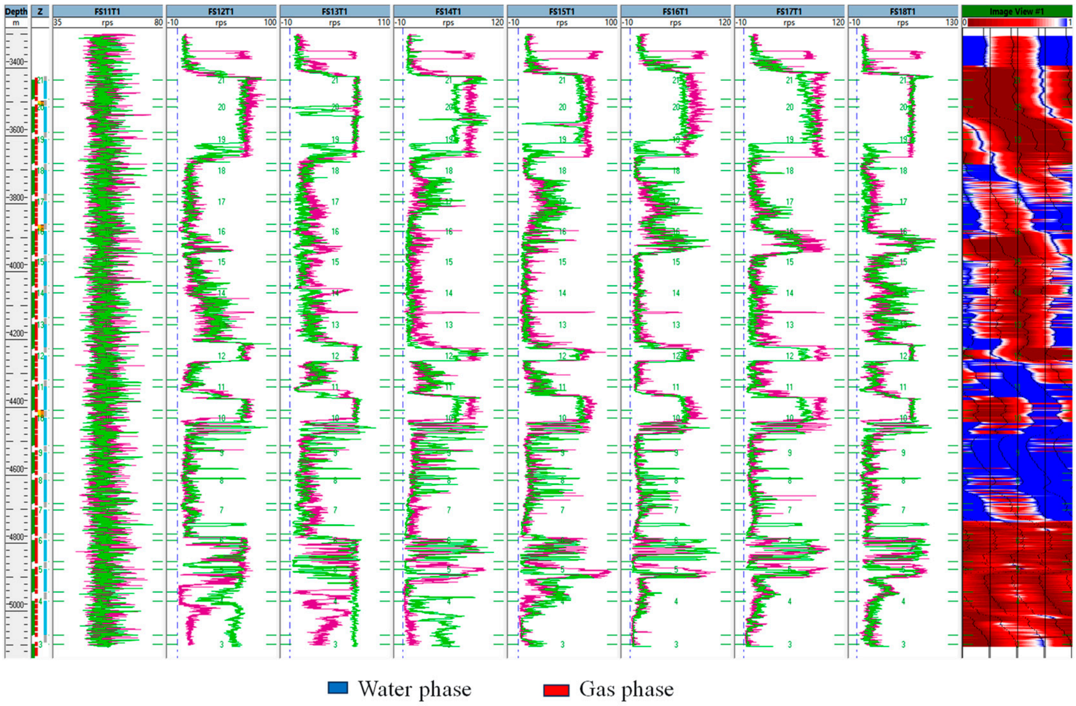

Figure 12. Signals measured by Doppler sensor. The blue color in the figure indicates the water phase, and the red color indicates the gas phase. The Doppler sensor indicates a phase change when there is a significant fluctuation in the detected signal, as shown in the last column.

The data depicted in Figure 13 reveal that in the overall well section, sections 1–3 contribute 12.94% of combined gas production, while sections 1–7 collectively account for 34.30%. The remaining 65.70% is attributed to sections 8–21. Notably, segments 21, 20, 19, 12, 11, 10, 9, 5, and 4 exceed the average contribution rate. On the contrary, sections with lower production contributions are predominantly found in sections 16–13. This well exhibits relatively low water production, primarily emanating from sections 10 and 11.

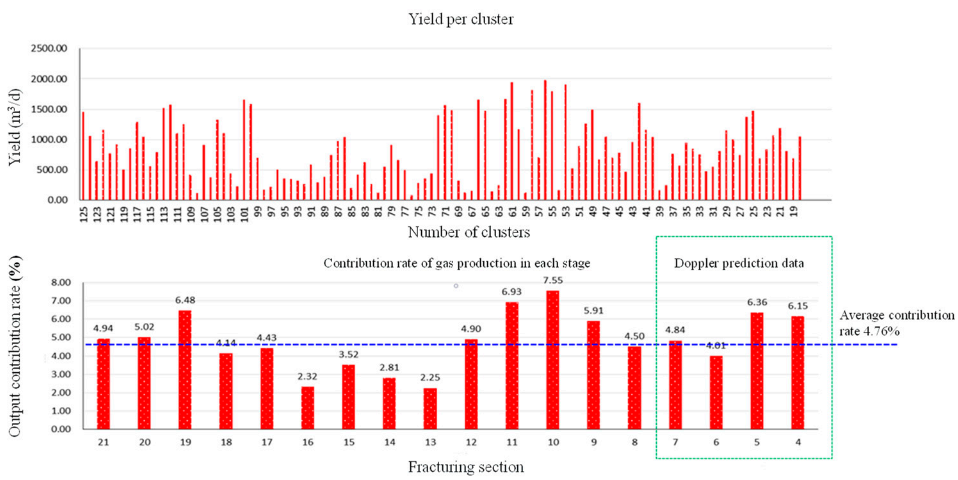

Figure 13. Doppler compensation data.

The FAST instrument boasts a length of approximately 0.86 m, and is primarily designed to ensure that all measurements are conducted within the same depth of environment, thereby guaranteeing the accuracy of the results. Its remarkable compactness renders it significantly more advantageous compared to the FSI, whose instrument string length can be up to ten times longer than that of the FAST.

Under identical conditions, FAST offers an extensive measurement range, as evidenced in Figure 14. The upper limit for valid data measurements with FSI is 4600 m, whereas FAST extends its measuring capacity to 4700 m. This disparity underscores the distinctive edge of FAST in acquiring data at greater depths.

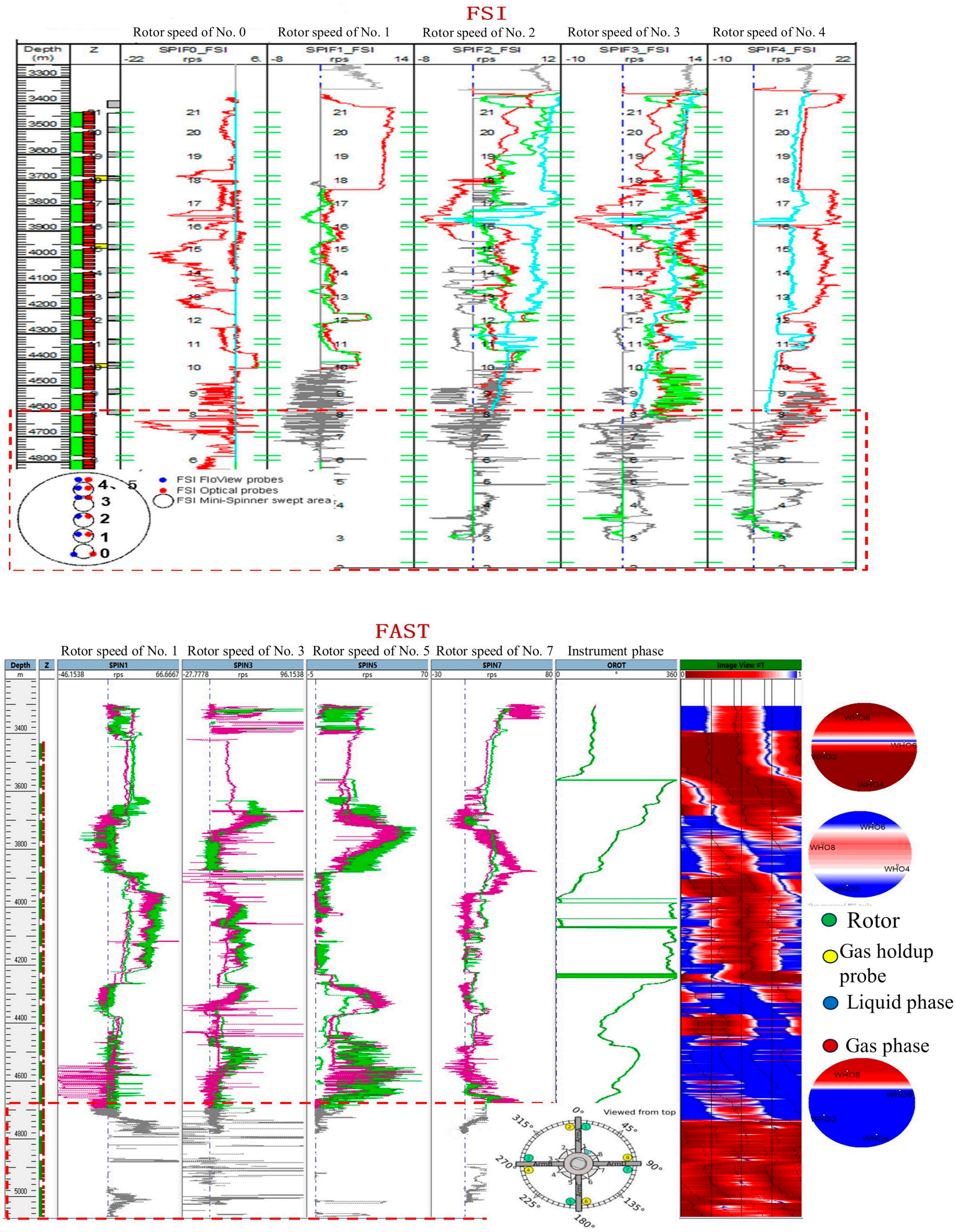

Figure 14. FSI 4600 m rotor data vs. FAST 4700 m rotor data. The graph shows the quality of the test data for the 5 rotors of the FSI instrument and the 4 rotors of the FAST instrument, and the red dashed box shows that FAST measures 100 more data points than FSI.

5. Conclusions

The application of horizontal well production logging technology has laid a solid foundation for the development and optimization of oil and gas fields. With the emergence of array-type production logging instruments and the advancement of horizontal well interpretation models, this technology is of great significance in guiding the next stage of oil and gas well development. Through an extensive study of two types of array logging instruments applied to one well, we draw the following conclusions:

The appearance of array logging instruments effectively solves the difficulties of traditional logging instruments when encountering oil, gas, and water three-phase stratification in inclined or horizontal wells. The multi-parameter evaluation method proposed in this paper can obtain measurement results more accurately. It can not only deeply interpret the degree of gas and fluid contribution in each shothole section, but can also clearly show the main water-producing zones. This provides a more specific basis for evaluating reservoir production at each level. The proposed method has the potential for wider application in terms of measurement range and adaptation to various well conditions.

Author Contributions: Writing—review and editing, R.L. and Q.D.; conceptualization, J.L.; formal analysis, D.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Key Program of the Hubei Provincial Department of Education, No. D20221303; the Natural Science Foundation of Hubei Province, No. 2022CFB700; the Open Fund of the Hubei Key Laboratory of Drilling and Production Engineering for Oil and Gas (Yangtze University), No. YQZC202206; and the Open Foundation of Cooperative Innovation Center of Unconventional Oil and Gas, Yangtze University (Ministry of Education & Hubei Province), No. UOG2022-03.

Institutional Review Board Statement: This study did not require ethical approval.

Informed Consent Statement: This study did not involve humans.

Data Availability Statement: The data underlying the results presented in this paper are not publicly available at this time, but may be obtained from the authors upon reasonable request.

Conflicts of Interest: All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Yang, D. An Array Production Logging Instrument and Logging System. Guangdong Province CN113685169A, 23 November 2021.
2. Xu, L.; Xu, W.; Cao, Z.; Liu, X.; Hu, J. Multiple parameters' estimation in horizontal well logging using a conductance-probe array. *Flow Meas. Instrum.* **2014**, *40*, 192–198. [CrossRef]
3. Dejia, D.; Wei, P.; Jun, M.; Shuang, A.; Ying, H. Production Logging Application in Fuling Shale Gas Play in China. In Proceedings of the 2016 SPE Asia Pacific Oil & Gas Conference and Exhibition, Perth, Australia, 25–27 October 2016.
4. Dejia, D.; Jun, M.; Ying, H.; Shuang, A.; Tongyi, Z.; Wei, P. Analysis and application of production logging data in shale gas well. In Proceedings of the SPE Europec featured at 79th EAGE Conference and Exhibition, Paris, France, 12 June 2017.
5. Kaleem, W.; Tewari, S.; Fogat, M.; Martyushev, D.A. A Hybrid Machine Learning Approach Based Study of Production Forecasting and Factors Influencing the Multiphase Flow through Surface Chokes. *Petroleum* **2023**, *in press*. [CrossRef]
6. Salnikova, O.L.; Chernykh, I.A.; Martyushev, D.A.; Ponomareva, I.N. Features of determining filtration parameters of complex carbonate reservoirs at their operation by horizontal wells. *Bull. Tomsk. Polytech. Univ. Geo Assets Eng.* **2022**, *334*, 138–147. [CrossRef]
7. Soromotin, A.V.; Martyushev, D.A.; Stepanenko, I.B. Application of machine learning methods to forecast the rate of horizontal wells. *SOCAR Proc.* **2023**, *1*, 70–77. [CrossRef]
8. Zaitsev, R.A.; Martyushev, D.A. Justification of the optimal type of well completion profile based on a retrospective assessment of the technical and economic performance indicators. *Georesursy* **2023**, *25*, 119–129. [CrossRef]
9. Davarpanah, A.; Mirshekari, B.; Jafari Behbahani, T.; Hemmati, M. Integrated production logging tools approach for convenient experimental individual layer permeability measurements in a multi-layered fractured reservoir. *J. Pet. Explor. Prod. Technol.* **2018**, *8*, 743–751. [CrossRef]
10. Chitre, S.; Mustafa, H.; Anurag, A.K.; Bazuhair, A.K.; Kuliyev, M.; Javid, K.; Anjum, U.; Sookram, N.; AlHaji, L.; Al-Kindi, Z.; et al. Looking at the Bigger Picture-Better Understanding of Well Behavior through Integration of Petrophysical, Production Logging and Corrosion Evaluation Data in a Challenging Environment, Ensuring Maximum Well Life and Overall Productivity. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 9–12 November 2020.
11. Liao, L.; Zhu, D.; Yoshida, N.; Hill, A.D.; Jin, M. Interpretation of array production logging measurements in horizontal wells for flow profile. In Proceedings of the SPE Annual Technical Conference and Exhibition, New Orleans, LA, USA, 30 September 2013.
12. Zhu, D.; Hill, D.; Zhang, S. Using temperature measurements from production logging/downhole sensors to diagnose multistage fractured well flow profile. In Proceedings of the SPWLA 59th Annual Logging Symposium, London, UK, 2 June 2018.
13. Song, W.; Chen, H.; Zhang, Q.; Zhang, J. Design and implementation of the array logging tool on horizontal production logging. *Math. Probl. Eng.* **2020**, *2020*, 1–7. [CrossRef]

14. Ahmad, N.A.; Chieng, Z.H.; Jelie, A.; Abdul Rahman, H.; MAmin, M.F.; Foo, N.K.H.; Zakeria, A.F.; Sidek, S.; Yahya, F.; Ramli, S.; et al. Array Production Survey Accurately Pinpoints Water Shut-Off Location and Strengthen the Understanding on Remaining Potential of a Giant Carbonate Gas Field, Offshore East Malaysia. In Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition, Adelaide, Australia, 17–19 October 2022.
15. Vu-Hoang, D.; Faur, M.; Marcus, R.; Cadenhead, J.; Besse, F.; Haus, J.; Wadjiri, A. A novel acquisition system for production logging in multiphase horizontal wells. In Proceedings of the AAPG International Conference, Cancun, Mexico, 6–9 September 2004.
16. Li, Y.B. The production logging array imager is studied in horizontal well. *Electronic Testing* **2017**, *17*, 85+70.
17. Pang, W.; Di, D.; Mao, J.; Zhang, T.; He, Y.; Shuang, A. Production Logging of Shale Gas Well in China. In Proceedings of the SPE Asia Pacific Hydraulic Fracturing Conference, Beijing, China, 24–26 August 2016.
18. Guoping, Y.; Heng, L.; Yueyuan, Z. Application of Array Image Tools of Production Logging in Horizontal Wells. *Pet. Tubul. Goods Instrum.* **2016**, *2*, 59–62+66.
19. Heddleston, D.C.; Haggerty, M. Shale gas horizontal production logging measurements and challenges. In Proceedings of theTight Gas Completions Conference, San Antonio, TX, USA, 2 November 2010.
20. Boyer, R.; Findlay, C., II; Suparman, F.N.U.; Sudija, J.; Reyes, R. Production array logs in bakken horizontal shale play reveal unique performance based on completion technique. In Proceedings of the SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, 8 October 2012.
21. Al-Ebrahim, A.; Al-Bader, H.; Al-Nabhan, A.R.; Duggirala, V.S.; Ayyavoo, M. Using e-coiled tubing for production logging while n2 lifting in horizontal/deviated exploratory well. In Proceedings of the SPE Kuwait Oil & Gas Show and Conference, Kuwait City, Kuwait, 15 October 2017.
22. Xuangang, M.; Wang, W.; Shen, Z.; Xiong, J.; Zhang, H. Production logging via coiled tubing fiber optic infrastructures (fsi) and its application in shale gas wells. *Arab. J.* **2019**, *12*, 1–7.
23. Khong, C.K.; Sookram, N.; Mukerji, P.; Cruz, M.; Martins, F.; Zett, A. Robust diagnostics optimize decisions on innovative deepwater gravel-pack interventions for water conformance. In Proceedings of the SPE Nigeria Annual International Conference and Exhibition, Virtual, 11 August 2020.
24. Gysen, A.; Gysen, M.; Zett, A.; Webster, M.; Yusti, G. Production logging in highly deviated and horizontal wells: Moving from qualitative to quantitative answers. In Proceedings of the SPE Annual Technical Conference and Exhibition, Florence, Italy, 19 September 2010.
25. Wang, C.; Liu, C.; Yu, S. Gas production profile logging technology of horizontal well with MAPS array imaging and its application in Zhao-Tong National Shale Gas Demonstration Area. *Nat. Gas. Ind.* **2021**, *41*, 94–99.
26. Waqar, K.; Jambunathan, V.; Quintero, L. Pitfalls of running conventional production logging in horizontal/highly deviated wells: A case study. In Proceedings of the SPWLA Annual Logging Symposium, Long Beach, CA, USA, 18–22 July 2015.
27. Pang, W.; Du, J.; Zhang, T.; Mao, J.; Di, D. Production performance modeling of shale gas wells with non-uniform fractures based on production logging. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dubai, United Arab Emirates, 26 September 2016.
28. Abbassi, L.; Tavernier, E.; Donzier, E.; Gysen, A.; Gysen, M.; Chen, C.K.; Zied, A.; Cedillo, G. Efficiency improvements in production profiling using ultracompact flow array sensing technology. *Petrophysics* **2018**, *59*, 457–488. [CrossRef]
29. Donzier, E.; Tavernier, E.; Abbassi, L. Probe, Sonde and Method for Producing Signals Indicative of Local Phase Composition of a Fluid. U.S. Patent 9952192, 24 April 2018.
30. González, J.W.; Linares, A.J.; Rodriguez, D.A.; Rivera, G.O.; Schoepf, V.M.; Abbassi, L. Quantification of fluid production distribution in deviated wells with high gas-liquid ratio using a flow array sensing tool. In Proceedings of the SPE Argentina Exploration and Production of Unconventional Resources Symposium, Buenos Aires, Argentina, 20 March 2023.
31. Donovan, G.; Kamath, S.; Tanis, E.; Abbassi, L.; Gysen, A. Third generation production logging technologies enhance inflow profiling in deepwater Gulf of Mexico Reservoirs. In Proceedings of the SPE Annual Technical Conference and Exhibition, Calgary, AB, Canada, 30 September–2 October 2019.
32. Katterbauer, K.; Aramco, S.; Marsala, A.; Schoepf, V.; Abbassi, L. Doppler vs. Spinner PLT Sensing for Hydrocarbon Velocity Estimate by Deep-Learning Approach. In Proceedings of the SPWLA Annual Logging Symposium, Lake Conroe, TX, USA, 17–20 May 2021.
33. Zheng, S.; Yang, M.; Kang, Z.; Liu, Z.; Long, X.; Liu, K.; Li, X.; Zhang, S. Controlling factors of remaining oil distribution after water flooding and enhanced oil recovery methods for fracture-cavity carbonate reservoirs in tahe oilfield. *Pet. Explor. Dev.* **2019**, *46*, 786–795. [CrossRef]
34. Ma, X.; Li, H.; Luo, H.; Nie, S.; Gao, S.; Zhang, Q.; Yuan, F.; Ai, W. Research on well selection method for high-pressure water injection in fractured-vuggy carbonate reservoirs in tahe oilfield. *J. Pet. Sci. Eng.* **2022**, *214*, 110477. [CrossRef]
35. Li, N.; Dai, J.; Liu, C.; Liu, P.; Zhang, Y.; Luo, Z.; Zhao, L. Feasibility study on application of volume acid fracturing technology to tight gas carbonate reservoir development. *Petroleum* **2015**, *1*, 206–216. [CrossRef]
36. Alhuraishawy, A.K.; Bai, B.; Imqam, A.; Wei, M. Experimental study of combining low salinity water flooding and preformed particle gel to enhance oil recovery for fractured carbonate reservoirs. *Fuel* **2018**, *214*, 342–350. [CrossRef]
37. Guo, J.; Gou, B.; Qin, N.; Zhao, J.; Wu, L.; Wang, K.; Ren, J. An innovative concept on deep carbonate reservoir stimulation: Three-dimensional acid fracturing technology. *Nat. Gas Ind. B* **2020**, *7*, 484–497. [CrossRef]

38. Hou, B.; Chang, Z.; Fu, W.; Muhadasi, Y.; Chen, M. Fracture initiation and propagation in a deep shale gas reservoir subject to an alternating-fluid-injection hydraulic-fracturing treatment. *SPE J.* **2019**, *24*, 1839–1855. [CrossRef]
39. Zhou, F.; Su, H.; Liang, X.; Meng, L.; Yuan, L.; Li, X.; Liang, T. Integrated hydraulic fracturing techniques to enhance oil recovery from tight rocks. *Pet. Explor. Dev.* **2019**, *46*, 1065–1072. [CrossRef]
40. Sun, X.; Bai, B. Comprehensive review of water shutoff methods for horizontal wells. *Pet. Explor. Dev.* **2017**, *44*, 1022–1029. [CrossRef]
41. Seright, R.; Brattekas, B. Water shutoff and conformance improvement: An introduction. *Pet. Sci.* **2021**, *18*, 450–478. [CrossRef]