Fault Diagnosis Model and Application of Water Injection Well Based on SPC Rules and Real-time Data Fusion

Chunfeng Zheng¹, Ang Li¹, Song Wang², Cheng An¹, Chaodong Tan²,*, Guanghao Du² and Huizhao Niu³

¹Engineering Technology Branch of CNOOC Energy Development Co., Ltd., Tianjin 300452; ²China University of Petroleum (Beijing), Beijing 102249; ³Beijing Yadan Petroleum Technology Development Co., Ltd., Beijing 102200, China

*Corresponding author email: tanchaodong@cup.edu.cn

Abstract. Based on the Extended SPC rules and real-time data fusion, the operating fault diagnosis model and application research of water injection wells were carried out. The historical operating parameters of water injection wells were studied, a multi-parameter rule fault chart was established, and the weight factors of fault diagnosis parameters were obtained based on expert Pcores. A operating fault diagnosis model of water injection wells based on SPC rules and real-time data fusion was constructed. The example analysis shows that the model has good adaptability in Bohai oilfield, can diagnose the fault of water injection wells in real time, quantitatively and accurately, and improves the intelligent level of real-time fault diagnosis of water injection wells.

Keywords: Water injection well; SPC rule; Data fusion; Multi-reference chart; Fault diagnosis.

1. Introduction

With the continuous development of oil field, oil well development faces challenges such as formation energy deficit and rapid decline in production. At this time, water injection has become the main means for oil wells to increase production [1]. However, during the operation of water injection wells, serious failures such as water nozzle blockage, stratum blockage, and tubing leakage often occur. Therefore, engineers and managers need to keep abreast of the working conditions of water injection wells in time and quickly diagnose the type of abnormal conditions.

SPC is the abbreviation of Statistical Process Control [2]. It refers to the analysis and real-time monitoring of products based on statistical analysis techniques and control charts, and early warnings of abnormal trends in the production process, which can scientifically distinguish the normal fluctuations and abnormal fluctuations of key product indicators during the production process. In recent years, fault diagnosis technology based on SPC rules has been widely used in the industry. Nong Y et al. [3] developed a computationally efficient and Pcalable Chi-Square () distance monitoring (CSDM) process based on standard multivariable SPC technology. This is used to monitor large-Pcale and complex process data for fault diagnosis; Sun, B. et al. [4] studied the fault diagnosis method of air cooler with air flow change, using SPC to measure and analyse its changes for fault detection and diagnosis; Rossi T et al. [5] proposed a statistics-based fault detection and diagnosis method for vapor compression air-conditioning. The difference between the measured thermodynamic state and the predicted state obtained from the normal performance model (residual error) will be used as a performance indicator for fault detection and diagnosis. Then, by comparing the change in the direction of each residual with a set of general rules specific to each fault, diagnosis can be made; Jiang C et al. [6] proposed SPC fault
diagnosis and prediction methods based on principal component analysis (PCA) and long short-term memory (LSTM) neural network based on SPC technology; Martin E.B. et al. [7] is a process monitoring and fault detection method based on multivariate SPC. The principle of this method is that a fault will cause changes in some physical parameters and measured values, which in turn will lead to changes in some model parameters or states. The above research shows that the fault diagnosis technology based on SPC technology can accurately and real-time fault diagnosis, which provides basic theory and technical support for the diagnosis of water injection well conditions. Aiming at the complexity, diversity and nonlinearity of the downhole environment, insufficient data utilization of existing water injection well failure prediction methods, and low model accuracy, this paper proposes a water injection well production failure diagnosis method based on SPC rules and real-time data fusion. This method realizes real-time and accurate diagnosis of the faults of water injection wells, and provides theoretical and practical basis for fault diagnosis of injection-production wells and injection-production equipment in oil fields.

2. Establishment of Diagnosis Model for Production Failure of Water Injection Well

The fault diagnosis flowchart of water injection well is shown in Figure 1, which is mainly divided into three steps: (1) The real-time operating parameters collected by the water injection well are input into the SPC rule model of the water injection working condition through the failure time window to obtain the change law of the parameters of the water injection well; (2) Establish a fault diagnosis model for water injection wells by using abnormal rule plates and fault diagnosis weight factors; (3) Verify that the accuracy of the model is qualified. If it is qualified, a fault diagnosis system for water injection wells will be formed. Otherwise, the abnormal rule plate, fault diagnosis weight factor or fault diagnosis time window will be adjusted to reform the fault diagnosis model for water injection wells.

![Figure 1. Flow chart of fault diagnosis for water injection well.](image1)

![Figure 2. SPC control chart.](image2)

2.1. Establishment of SPC Rules for Water Injection Conditions

Let $W_i$ be a sample, assume that the mean of $W_i$ is $u_i$ and the standard deviation is $\sigma_i$. So the control chart is shown in Figure 2. The centre line is CL, the upper control line is UCL, and the lower control line is LCL. The calculation is as follows:

$$
\begin{align*}
UCL &= u_i + \sigma_i \\
CL &= u_i \\
LCL &= u_i - \sigma_i 
\end{align*}
$$

(1)

In the formula, K is the interval width between the centre line and the control limit expressed in the unit of standard deviation.

The eight different criteria commonly used in the national standard GB/T4901-2001 "Conventional Control Chart" are shown in Table 1.
Table 1. Standard SPC eight different criteria.

| SPC Guidelines | Specific rules |
|----------------|----------------|
| Guideline 1    | At least one point is outside zone A |
| Guideline 2    | At least 9 consecutive points are distributed on the same side of CL |
| Guideline 3    | Rise or fall for at least 6 consecutive points |
| Guideline 4    | At least 14 consecutive points fluctuate up and down |
| Guideline 5    | At least 2 of the 3 consecutive points are on the same side of CL and not in zone B |
| Guideline 6    | At least 4 of the 5 consecutive points are on the same side of CL and not in zone C |
| Guideline 7    | 15 points are in Zone C on both sides of CL |
| Guideline 8    | At least 8 consecutive points are distributed on and off the CL line and not in zone C |

When the SPC criterion is applied to the fault diagnosis process of water injection wells, it is not only hoped to be able to distinguish the abnormal trend of operating parameters, but also hope to be able to describe its changing trend in detail. Therefore, we slightly modified the standard SPC criteria, and split the eight rules into 13 criteria, seven types of trend characteristics (Rapid rise, Moderate rise, Slight rise, Rapid drop, Moderate drop, Slight drop, Wave). As shown in Table 2, an extended SPC rule is formed.

Table 2. Extended SPC rules.

| Serial number | SPC Rule | Trend characteristics | Specific rules |
|---------------|----------|-----------------------|----------------|
| 1             | Rule 1   | Rapid rise            | A point falls on the centre line CL and outside of zone A |
| 2             | Rule 1   | Rapid drop            | A point falls below the centre line CL and outside of zone A |
| 3             | Rule 2   | Slight rise           | The value of at least 9 consecutive points is greater than CL |
| 4             | Rule 2   | Slight drop           | The value of at least 9 consecutive points is less than CL |
| 5             | Rule 3   | Moderate rise         | 6 consecutive points increase, and the last point is outside of zone A |
| 6             | Rule 3   | Moderate drop         | Decrease by 6 consecutive points and the last point is outside Zone A |
| 7             | Rule 4   | Wave                  | At least 14 consecutive points are distributed on both sides of CL up and down, and the maximum minus the minimum is greater than 3UCL-6CL |
| 8             | Rule 5   | Wave                  | At least 2 of the 3 points have values greater than 2UCL-3CL |
| 9             | Rule 5   | Wave                  | At least 2 of the 3 points have values less than 2LCL-CL |
| 10            | Rule 6   | Slight rise           | At least 4 of the 5 points have values greater than UCL |
| 11            | Rule 6   | Slight drop           | At least 4 of the 5 points have values less than LCL |
| 12            | Rule 7   | Wave                  | 15 points are in upper and lower area C |
| 13            | Rule 8   | Wave                  | 8 consecutive are not in upper and lower zone C |

2.2. Construction of Multi-parameter Rule Failure Chart

Through the analysis of some typical characteristic parameter changes of water injection wells, combined with the investigation and analysis of typical failures of water injection wells and the extended SPC rules, the change rule chart of the characteristic parameters of 7 different faults in the production of water injection wells is summarized. As shown in Table 3. This provides a theoretical basis for fault diagnosis.
Table 3. Multi-parameter curve rule chart for water injection wells.

| Fault type                                      | PP | TP | CP | DAIV | DP | IF | WAI | PFN | PBN | TWAS |
|------------------------------------------------|----|----|----|------|----|----|-----|-----|-----|------|
| Water distributor or nozzle blocked            | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Wellbore scaling                               | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Formation blocked                              | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Water distributor or nozzle getting bigger     | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Top packer or insert seal failure              | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Tubing leakage                                 | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Distributor or nozzle falls off                | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Nozzle blocked                                 | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Nozzle getting bigger                          | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Nozzle falls off                               | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Packer failure                                 | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Formation blocked                              | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |
| Normal                                         | N  | N  | N  | N    | N  | N  | N   | N   | N   | N    |

In the table, PP means Pipeline pressure, TP means Tubing pressure, CP means Casing pressure, DAIV means Daily actual injection volume, DP means Daily actual injection volume/tubing pressure, IF means Instantaneous flow, WAI means Water absorption index, PFN means Pressure in front of nozzle, PBN means Pressure behind nozzle, and TWAL means Total water absorption of small layer.

In the table: N indicates that this operating condition has nothing to do with this parameter;  indicates rapid rise;  indicates moderate rise; indicates slight rise; indicates rapid decline;  indicates moderate decline; indicates slight decline; indicates basically unchanged.

If you use ±3 to indicate a rapid increase (decrease), ±2 to indicate a moderate increase (decrease), ±1 to indicate a slight increase (decrease), 0 to indicate basically unchanged, and +∞ to indicate N. Then get the digital rule plate of working condition, as shown in Table 4.

Table 4. Working condition digital rule plate.

| Fault type                                      | PP | TP | CP | DAIV | DP | IF | WAI | PFN | PBN | TWAS |
|------------------------------------------------|----|----|----|------|----|----|-----|-----|-----|------|
| Water distributor or nozzle blocked            | +∞ | 3  | 0  | -3   | -3 | -3 | +∞  | +∞  | +∞  | +∞   |
| Wellbore scaling                               | +∞ | 1  | 0  | 0    | 1  | 0  | -1  | +∞  | +∞  | +∞   |
| Formation blocked                              | +∞ | 1  | 0  | -2   | -3 | +∞ | -3  | +∞  | +∞  | +∞   |
| Water distributor or nozzle getting bigger     | +∞ | -1 | 0  | 1    | 2  | 1  | 1   | +∞  | +∞  | +∞   |
| Top packer or insert seal failure              | 0  | -1 | 2  | 0    | 1  | 1  | 2   | +∞  | +∞  | +∞   |
| Tubing leakage                                 | -2 | 2  | 2  | 1    | 2  | 1  | 3   | +∞  | +∞  | +∞   |
| Distributor or nozzle falls off                | +∞ | -3 | 3  | 3    | 3  | 3  | 3   | +∞  | +∞  | +∞   |
| Nozzle blocked                                 | +∞ | +∞ | +∞ | +∞   | +∞ | +∞ | +∞  | +∞  | +∞  | +∞   |
| Nozzle getting bigger                          | +∞ | +∞ | +∞ | +∞   | +∞ | +∞ | +∞  | +∞  | +∞  | +∞   |
| Nozzle falls off                               | +∞ | +∞ | +∞ | +∞   | +∞ | +∞ | +∞  | +∞  | +∞  | +∞   |
| Packer failure                                 | +∞ | +∞ | +∞ | +∞   | +∞ | +∞ | +∞  | +∞  | +∞  | +∞   |
| Formation blocked                              | +∞ | +∞ | +∞ | +∞   | +∞ | +∞ | +∞  | +∞  | +∞  | +∞   |
| Normal                                         | 0  | 0  | 0  | 0    | 0  | 0  | 0   | 0   | 0   | 0    |

2.3. Fault Diagnosis Parameter Weight Factor

The weighting factor is used to quantify the contribution of each parameter under each working condition to this working condition. Because it is a fraction or ratio of a unit value, the sum of all contributions under each working condition is 1. As shown in Table 5. For example: when the water distributor or the water nozzle is blocked, it is expected that the most affected parameter will be the casing pressure, so the weighting factor of the casing pressure is assigned as 0.31. On the contrary,
pipeline pressure, pressure in front of the nozzle, pressure behind the nozzle and total water absorption of small layers have the least influence. In this working condition, the sum of the weight values of all parameters is 1. This table is obtained based on expert Pcores and actual conditions on site. These factors should be calibrated regularly with actual water injection well events.

### Table 5. Weight factor of water injection well fault diagnosis parameter.

| Fault type                          | PP  | TP  | CP  | DAIV | DP  | IF  | WAI | PFN | PBN | TWAS |
|-------------------------------------|-----|-----|-----|------|-----|-----|-----|-----|-----|-------|
| Water distributor or nozzle blocked | 0.00| 0.27| 0.31| 0.18 | 0.12| 0.08| 0.04| 0.00| 0.00| 0.00  |
| Wellbore scaling                    | 0.00| 0.23| 0.28| 0.20 | 0.04| 0.16| 0.09| 0.00| 0.00| 0.00  |
| Formation blocked                   | 0.00| 0.28| 0.16| 0.13 | 0.24| 0.00| 0.19| 0.00| 0.00| 0.00  |
| Water distributor or nozzle Getting | 0.00| 0.29| 0.23| 0.12 | 0.13| 0.15| 0.08| 0.00| 0.00| 0.00  |
| Top packer or insert seal failure   | 0.24| 0.13| 0.15| 0.06 | 0.21| 0.09| 0.12| 0.00| 0.00| 0.00  |
| Tubing leakage                      | 0.29| 0.21| 0.12| 0.05 | 0.12| 0.15| 0.06| 0.00| 0.00| 0.00  |
| Distributor or nozzle falls off     | 0.28| 0.21| 0.12| 0.14 | 0.03| 0.27| 0.00| 0.00| 0.00| 0.00  |
| Nozzle blocked                      | 0.00| 0.00| 0.00| 0.00 | 0.00| 0.00| 0.45| 0.27| 0.28| 0.00  |
| Nozzle getting bigger               | 0.00| 0.00| 0.00| 0.00 | 0.00| 0.32| 0.47| 0.21| 0.25| 0.00  |
| Nozzle falls off                    | 0.00| 0.00| 0.00| 0.00 | 0.00| 0.30| 0.45| 0.25| 0.65| 0.00  |
| Packer failure                      | 0.00| 0.00| 0.00| 0.00 | 0.00| 0.12| 0.23| 0.65| 0.00| 0.00  |
| Formation blocked                   | 0.00| 0.00| 0.00| 0.00 | 0.36| 0.36| 0.64| 0.00| 0.00| 0.00  |
| Normal                              | 0.10| 0.10| 0.10| 0.10 | 0.10| 0.10| 0.10| 0.10| 0.10| 0.10  |

2.4. Fault Diagnosis Model
Let $O_i$ be a certain working condition of the water injection well, $P_j$ is a certain operating parameter of the water injection well, and $\omega_{O_ip_j}$ is the weighting factor of the parameter $P_j$ corresponding to the working condition $O_i$, $b_{O_ip_j}$ is the change trend of the parameter $P_j$ corresponding to the working condition $O_i$ in the standard plate, $c_j$ is the change trend of a certain parameter in a certain period of time. It is assumed that the changing trend of cooking parameters in a certain period of time is shown in Table 6.

### Table 6. Parameter change trend of water injection well in a certain period.

| Fault type                          | PP  | TP  | CP  | DAIV | DP  | IF  | WAI | PFN | PBN | TWAS |
|-------------------------------------|-----|-----|-----|------|-----|-----|-----|-----|-----|-------|
| Trend                               | $c_1$| $c_2$| $c_3$| $c_4$| $c_5$| $c_6$| $c_7$| $c_8$| $c_9$| $c_{10}$|

Then the fault diagnosis model of water injection well is:

$$W_{O_i} = \sum_{j=1}^{n} \omega_{O_ip_j} \times \left(1 - |\text{sgn} \left( c_j - b_{O_ip_j} \right)|\right)$$  \hspace{1cm} (2)

In the formula: $W_{O_i}$ is the probability of $O_i$ occurrence of working condition, the larger $W_{O_i}$ means the greater the probability of occurrence of working condition $O_i$; $\text{sgn}(x)$ is the sign function.

3. Case Analysis
Taking a block in the QHD32-X oilfield as the research object, the current injection wells in this block are divided into pre-installed cables, concentric integration, and single-pole concentric injection; The water injection pressure of some water injection wells has a wide range of fluctuations, and there are abnormal water injection pressures; Some water injection wells also experienced increased casing pressure; The amount of water injection basically meets the injection requirements, and the suspended solids content is detected in the water quality index to exceed the standard. The data density of this well is 1 day/time, and the data within 90 days of this well is selected, as shown in Figure 3.
3.1. Fault Diagnosis Process
The fault diagnosis process of water injection well is shown in Figure 4, which is mainly divided into four steps: (1) Qualitative analysis: divide the time window for fault diagnosis of water injection wells, and use the SPC rule of water injection conditions to obtain the changing trend of parameters in the time window; (2) Standard plate comparison: match the obtained parameter change trend with the standard plate under a certain failure; (3) Quantitative analysis: Find out the weighting factors of each parameter under this type of fault in Table 5; (4) Fault diagnosis: use the fault diagnosis model to calculate the probability of the occurrence of the fault.

Figure 3. 90-day parameter change trend of water injection wells.

Figure 4. Flow chart of failure probability calculation.

3.2. Fault Diagnosis Result
Combined with Table 5 and formula (2), the probability of failure of water injection wells at 30 days, 60 days, and 90 days can be obtained. As shown in Table 7.
| Fault type                                      | 30 days | 60 days | 90 days |
|------------------------------------------------|---------|---------|---------|
| Water distributor or nozzle blocked            | 0%      | 0%      | 31%     |
| Wellbore Scaling                               | 59%     | 20%     | 28%     |
| Formation blocked                              | 28%     | 0%      | 16%     |
| Water distributor or nozzle Getting bigger     | 0%      | 0%      | 52%     |
| Top packer or insert seal failure              | 30%     | 30%     | 13%     |
| Tubing leakage                                 | 0%      | 0%      | 0%      |
| Distributor or nozzle falls off                 | 0%      | 0%      | 0%      |
| Nozzle blocked                                 | 0%      | 0%      | 0%      |
| Nozzle getting bigger                          | 0%      | 0%      | 0%      |
| Nozzle falling off                             | 0%      | 0%      | 0%      |
| Packer failure                                 | 23%     | 12%     | 0%      |
| Formation blocked                              | 0%      | 100%    | 0%      |
| Normal                                         | 70%     | 60%     | 30%     |
| Final failure                                  | Normal  | Formation blocked | Water distributor or nozzle Getting bigger |

As shown in Table 6, in the first 30 days, the probability of a normal water injection well is the largest, which is 70%; At 60 days, the probability of Formation blocked of the water injection well is the highest, which is 100%; At 90 days, the water injection well Water distributor or nozzle Getting bigger, which is 52%.

4. Conclusion

Based on conventional SPC rules and real-time data of water injection wells, 13 SPC rules for water injection well working condition have been formed, which provides basic conditions for the establishment of failure prediction models for water injection wells. Based on the analysis of the historical operating parameters of the water injection wells, the multi-parameter rule failure chart of the water injection wells was summarized; and based on the expert Peores and the actual production conditions on site, the failure prediction parameter weight factors were established. A diagnostic model for the operating conditions of water injection wells is constructed, which can perform accurate and real-time diagnosis of the operating conditions of water injection wells. Through field example analysis, it is proved that the water injection well production fault diagnosis model based on SPC rules and real-time data fusion has good adaptability in the Bohai Oilfield, and has good promotion and reference significance for fault prediction of production well and water injection well in other similar oilfields. In the future, the historical operation parameters of water injection wells will be analyzed, so as to expand SPC rules and fault diagnosis chart more accurately. At the same time, the weight factors of water injection well diagnosis parameters are further studied based on analytic hierarchy process and principal component analysis to make it more reasonable.

Acknowledgements

Fund project: Major special project of CNOOC Energy Development Co., Ltd. "Intelligent Technology Research for Injection and Production well" (NO.HFXMLZ-GJ2018-14); National Natural Science Foundation of China "Large-Pcale non-gathering oil well group production and pulling dispatch coordination optimization based on big data analysis"(No. 51974327).
References

[1] Su Y, et al. Study on and Application of Intelligent Regulation and Distribution Technology for Separate Water Injection Wells[M]. 2021.

[2] Gongxu Zhang. Two quality diagnosis theories and their applications[M]. BeiJing: Science Press, 2001.

[3] Nong Y, Parmar D, Borror C M. A Hybrid SPC Method with the Chi-square Distance Monitoring Procedure for Large: cale, Complex Process Data[J]. Quality and Reliability Engineering, 2006, 22(4):393-402.

[4] Sun, B., Luh, P.B. & O’Neill, Z. SPC and Kalman filter-based fault detection and diagnosis for an air-cooled chiller. Front. Electr. Electron. Eng. China 6, 412 (2011). https://doi.org/10.1007/s11460-011-0164-9

[5] Rossi T, Braun J. A Statistical, Rule-Based Fault Detection and Diagnostic Method for Vapor Compression Air Conditioners[J]. Hvac & R Research, 1997, 3(1):19-37.

[6] Jiang C, et al. Fault Diagnosis and Prediction Method of SPC for Engine Block Based on LSTM Neural Network[M]. 2019.

[7] Martin E.B., Morris A.J. (2000) Process Monitoring and Fault Detection Using Multivariate SPC. In: Patton R.J., Frank P.M., Clark R.N. (eds) Issues of Fault Diagnosis for Dynamic Systems. Springer, London. https://doi.org/10.1007/978-1-4471-3644-6_19

[8] Bermudez, F., et al. "Fuzzy Logic Application to Monitor and Predict Unexpected Behavior in Electric Submersible Pumps (Part of the KwIDF Project)." Paper presented at the SPE Intelligent Energy Conference & Exhibition, Utrecht, The Netherlands, April 2014. doi: https://doi.org/10.2118/167820-MS

[9] Al-Jasmi, A., Nasr, H., Goel, H. K., Moricca, G., Carvajal, G. A., Dhar, J., Querales, M., Villamizar, M. A., Cullick, A. S., Rodriguez, J. A., Velasquez, G., Yong, Z., Bermudez, F., and J. Kain. "ESP "Smart Flow" Integrates Quality and Control Data for Diagnostics and Optimization in Real Time." Paper presented at the SPE Digital Energy Conference, The Woodlands, Texas, USA, March 2013. doi: https://doi.org/10.2118/163809-MS