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Development, Application and Effect Evaluation of the Remote-controlled Automated Needle Valve Intermittent Production System in the L Well Block in China

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Abstract: In order to solve the problem of liquid loading, some water-produced gas wells use intermittent production mode to produce: shut in gas wells to restore energy during the closing phase, and open up to carry the liquid to surface by the high velocity gas during well opening phase, which is cost effective. However, some wells need frequent opening and closing or adjusting gas flow, manual opening and closing is easily influenced by external interference factors (road conditions, weather, public relation issue, etc.), and cannot guarantee production time for intermittent producing well. In order to realize the remote-control and automation for these wells, the remote-control automated needle valve intermittent production system was developed and successfully applied to the L well block. The gas rate, production time and economy before and after the smart needle valve installed was compared to do the performance assessment. The results show that: (1) the stability of the remote-control automated needle valve intermittent production system is good, and it can meet the requirments of the remote automated opening and closing of gas wells. (2) After the installation of the remote-controlled automated needle valve system, 71% of the gas wells have a stable gas increase, 100% of the gas wells have a higher well opening time, and the liquid unloading in the gas wells has been significantly improved. The average gas production increased from 1.75×10^4 m^3/d to 1.87×10^4 m^3/d, which was 6.86% higher than that before installation. The well opening time of 7 wells increased by 5.16% on average. (3) Compared with manual operation, the comprehensive economic performance of the remote-controlled automated needle valve opening system is more excellent. The remote-controlled automated needle valve opening system can remotely intelligently control the intermittent production of gas wells, which has significant economic benefits and high application value and worth further spreading.

Keywords: Liquid Loading, Deliquification and Gas Recovery, Intermittent Production, Remote-controlled Automated Needle Valve, Research and Development

1. Introduction

The L Well block is located in the southern margin of the Ordos Basin in China, a natural gas rich area, and is a tight gas reservoir [1]. After producing for a period, the formation pressure near the natural gas well wellbore gradually decreases, and the production drawdown decreases immediately, resulting in a decrease in the gas production rate. When the gas rate is lower than the critical liquid-carrying gas rate, the natural gas cannot carry liquid normally, resulting in the continuous accumulation of water droplets in the lower part of the wellbore. The flowing bottom hole pressure is increased, which ultimately reduces the gas production of a single well, resulting in liquid loading or even well killing by water, and the gas well cannot produce normally [2-4]. The completion string structure of some directional wells and horizontal wells in the L well block has no annulus, so the casing head pressure cannot be monitored, and drainage and gas recovery measures such as annular foam agent injection [5, 6], plunger gas lift [7] and gas lift cannot be used. In other wells, the wellbore has fallen fish issue and cannot install velocity string [8]. For this type of well, the drainage and gas recovery measures that can be used are limited. Improper handling can cause water lock damage [9-11] and even production termination.

Gas well intermittent production (referred to as intermittent production) is a simple, efficient and cost-effective production system for liquid loading gas wells, which is divided into manual opening & closing and remote-controlled automated opening & closing. Among them, it is time-consuming, labor-intensive, and inefficient to manipulate wells manually, and it is easily affected by traffic, weather, etc., and operators are exposed to dangerous driving and bad weather; Safety and personal health risks; the operation regime is difficult to be implemented sometimes, and the expected effect is not easy to be guaranteed [12, 13]; unit investment and maintenance costs are high, and remote control and information management cannot be achieved. These drawbacks have become weak points that restrict the upgrading of field production, technology and safety management in gas fields. In order to improve the efficiency of intermittent production, we developed remote-control intermittent production system and needle valves. According to the actual situation, we have carried out the research and development of remote-control automated needle valves and systems to reduce equipment and operating costs, and improve intermittent production. The effect of increasing production and efficiency is good, remote control and information management are also realized. Combined with production data, production engineers can accurately monitor the production status of gas wells, optimize the intermittent production regime, reduce tubing casing pressure differential, and improve gas and liquid production rate, gas well production time and ultimate recovery.

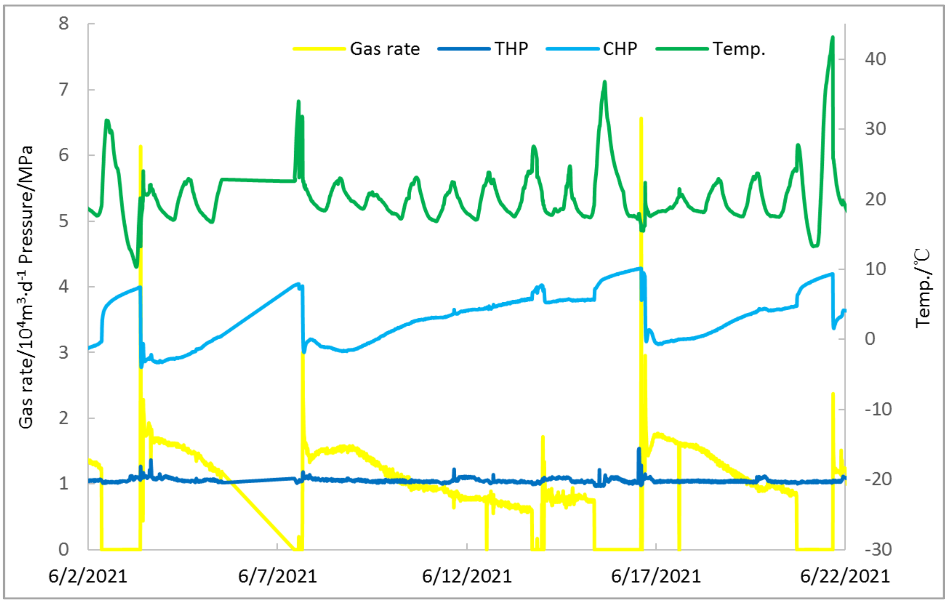

Figure 1. *Intermittent production schematic of Y5-2 well.*

2. The Principle of Intermittent Production

In the middle and late stages of gas well production, the formation pressure in the area near the wellbore has a large attenuation, and the drawdown decreases, resulting in a decrease in gas production rate. When the liquid cannot be carried normally, the droplets slip off the wellbore and accumulate at the bottom of the well, increasing the flowing bottom hole pressure, further reducing the drawdown, and ultimately reducing the gas production of a single well, resulting in water loading. The purpose of the intermittent production is to replace the accumulated liquid and gradually restore the wellbore energy through the gas migration after the well shut-in, then open the well after shut-in recovery for a period, and use high speed flowing gas to unload part of the accumulated liquid. Figure 1 shows the schematic diagram of the intermittent production of well Y4-2. Well Y4-2 is produced by 73.02mm tubing. According to the Turner and Li Min model [2, 3, 14], when the flowing wellhead pressure is 1.05MPa, the critical liquid-carrying gas flow speed is about 2.41 m/s, the critical liquid-carrying gas production rate is about 0.7×10^4 m^3/d (as shown by the green vertical dotted line in Figure 2). It can be seen from Figure 1 that when the gas rate at the wellhead is lower than the critical liquid-carrying gas rate, the gas rate of decreases gradually and the casing pressure rises, which is the typical liquid loading characteristics of natural gas well. At this time, the well is closed, the pressure is restored, the casing pressure rises, and the natural gas migrate to the wellbore, then the well is opened, the gas rate is higher than the critical liquid-carrying flow rate, part of water accumulated in bottom hole is unloaded to surface, the casing pressure drops, the gas well can produce normally for a short time, and then liquid loading gradually and periodically.

$$v_c = 2.5 \times \sqrt[4]{\frac{(\rho_L - \rho_G)\sigma}{\rho_G{}^2}} \tag{1}$$

In the formula: v_c——critical liquid-carrying velocity of gas well, m/s; ρ_L——liquid density, kg/m³; ρ_G——gas density, kg/m³; σ——gas-liquid surface tension, N/m;

The corresponding critical production formula is:

$$Q_c = 2.5 \times 10^8 \frac{APV_c}{ZT} \tag{2}$$

$$A = \frac{\pi}{4} d^2 \tag{3}$$

Where: Q_c——critical liquid-carrying flow rate, m³/d; A——cross-sectional area of tubing, m^2; d——inner diameter of tubing, m; p——pressure, MPa; T——temperature, K; Z——, the gas deviation factor under specific pressure and temperature conditions;

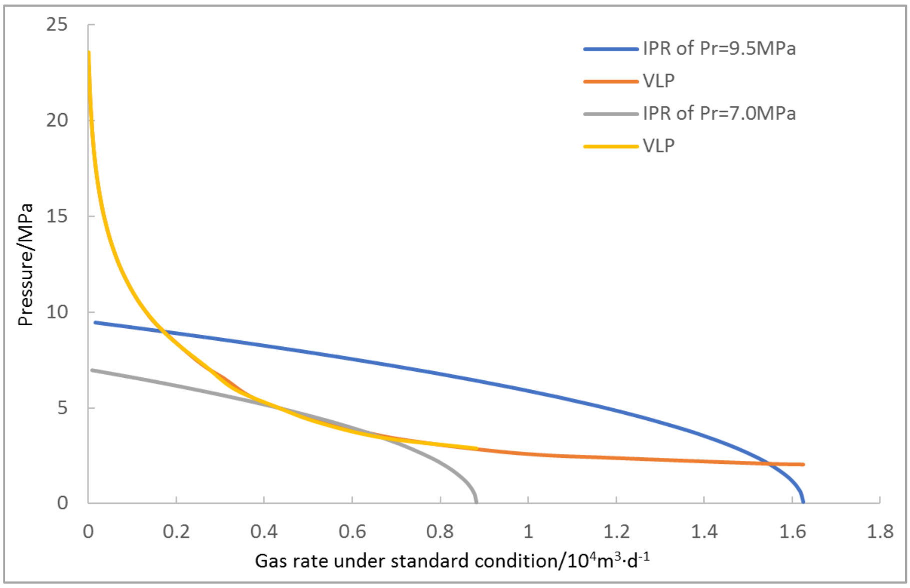

Figure 2. *IPR and VLP of well with water loading and water unloading during intermittent production.*

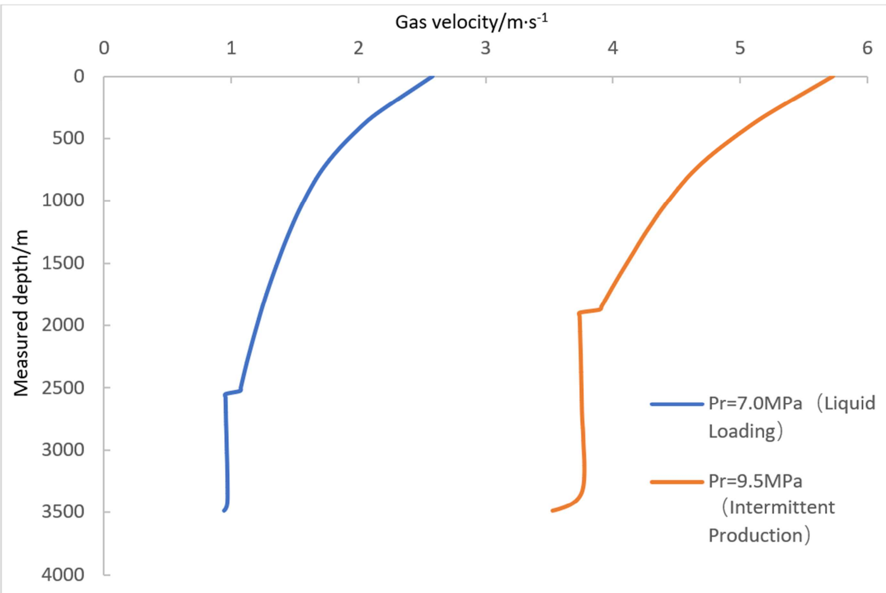

Figure 3. *Gas velocity distribution along wellbore of well with water loading and water unloading during intermittent production.*

The intermittent production is divided into two stages: open-well for production and shut-in for recovery. Figure 2 shows the inflow and outflow curves of the liquid loading state before shut-in (the pressure near the wellbore is 7MPa) and when the well is opened after the pressure is restored (the pressure near the wellbore is 9.5MPa). It can be seen from the figure that the gas rate at the intersection (coordination point) of the inflow and outflow curves is 0.67×10^4 m^3/d at late stage of the well-opening for production stage, i.e. liquid loading before the well is shut-in, which is less than the critical liquid-carrying gas rate (shown by the green dotted line), the gas rate gradually decreases or even drops to 0 because of liquid loading in the gas well; after the well shut-in to restore, the gas rate at the coordination point go up to 1.55×10^4 m^3/d, which is greater than the critical liquid-carrying gas rate in this state, and the gas well can carry out liquid and produce normally. The pressure in the area near the wellbore gradually decreases, and when the formation pressure reaches the liquid loading point, the gas well has signs of liquid loading again, and the well needs to be shut in for recovery, and the cycle begins again and again.

Figure 3 shows the gas flow velocity distribution along the wellbore of the liquid loading state before shut-in and the normal production state after the pressure is restored. It can be seen from the figure that in both cases, the gas flow velocity increases exponentially along the wellbore, but in the late stage of the well-opening production stage, that is, in the state of liquid loading before shut-in, the gas flow velocity is only 2.58m/s at the wellhead. Just exceeding the critical liquid-carrying flow velocity (about 2.41m/s) a little bit, the gas well cannot carry liquid normally, resulting in a gradual decrease in gas rate or even production stoppage; when the well is opened after shut-in recovery, the minimum gas flow velocity appears at the bottom of the well, which is 3.52 m/s and bigger than the critical liquid-carrying gas flow velocity in this state, the gas well can carry liquid normally. This explains the fundamental reason for the intermittent production liquid unloading.

3. Remote-Controlled Automated Needle Valve Intermittent Opening System

In order to achieve the remote-controlled automated opening and closing, the intermittent opening system needs to have real-time production data and other information as the basis for intermittent production management, as well as reliable and safe hardware, intelligent algorithm analysis and scalability (and seamless connection with oil and gas field intelligence). The remote-controlled automated needle valve system mainly includes remote-controlled automated needle valve, flow meter, remote transmission module, solar panel, communication box, pressure transformer, battery, and other parts. The modular design facilitates the selection of required functional modules according to actual needs. The composition diagram of the system is shown in Figure 4, in which the control system adopts the one-to-many method, and the same control platform is used in the same well pad to control the electronic valve actuators of different single wells on the well pad. Set the switch mode (time, pressure, pressure range) to open or close the electronic needle valve (adjust the opening scale) to realize remote-controlled automated management. It can realize remote constant pressure, timing, constant production flow rate and other switching modes.

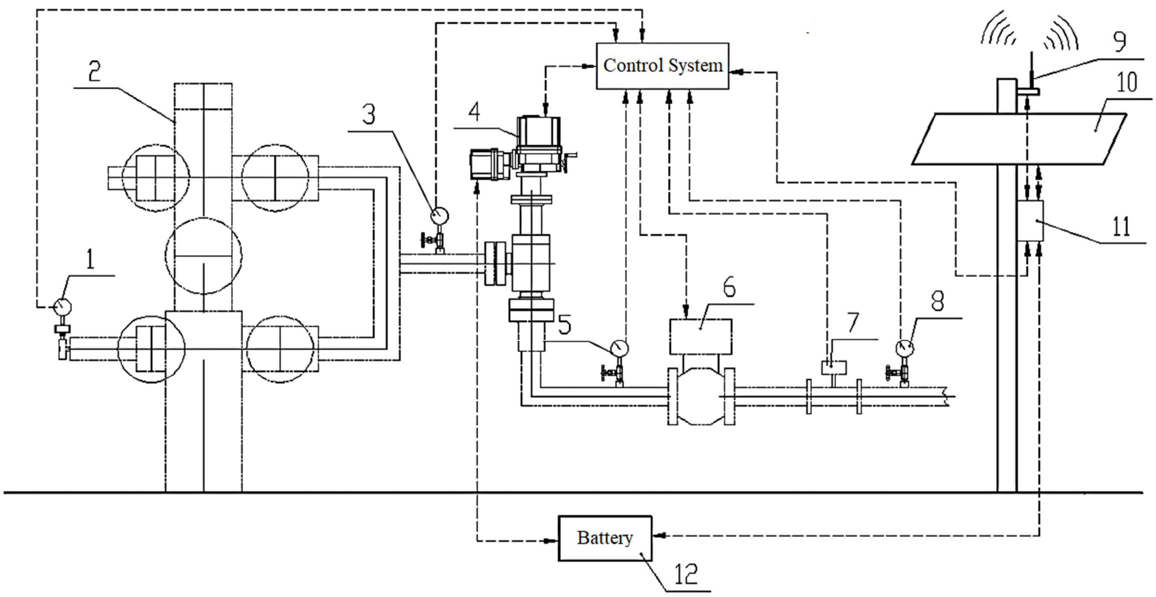

Figure 4. *Map of the remote-controlled automated needle valve intermittent opening system composition.*

1-Casing head pressure transformer 2-Christmas tree 3-Tubing pressure transformer 4-Remote-controlled automated needle valve 5-Pipeline pressure transformer 6-Gate valve 7-Flowmeter 8-Pressure transformer 9-Remote transmission module 10-Solar panel 11-Communication box 12-Battery.

According to the changes of production parameters such as critical liquid-carrying gas rate, tubing head pressure, casing head pressure, tubing-casing head pressure differential, and temperature, the time point of the intermittent opening and closing is determined, and the well can be shut in if three of the following conditions are satisfied at the same time: (1) The gas production of the gas well is less than the critical liquid-carrying rate; (2) The casing head pressure rises; (3) The pressure differential between the tubing and casing is greater than 2MPa; (4) The temperature of the pipeline changes with the ambient temperature (i.e. the temperature of the pipeline is close to or higher than the ambient temperature in summer, and the temperature of the pipeline is close to the ambient temperature in winter). The closing standard here is applied to the liquid loading gas well in the L well block with remarkable effect, accurate, stable and reliable performance, and high practicability.

In the later stage, it is planned to obtain the gas well production status and the optimal intermittent production system through the gas well liquid loading status and volume analysis, production history matching, production parameter prediction, and optimal production plan screening. The prediction results are displayed visually, and the production system is issued to the wellhead and automatically executed by the automated intermittent controller.

3.1. Remote-controlled Automated Needle Valve

The remote-controlled automated needle valve is one of the most important parts of this system. As shown in Figure 5, the internal structure is a conical valve core. The movement of the conical valve core changes the cross-sectional area of the fluid flow channel, so as to achieve the purpose of adjusting the flow rate. The main seal element of the valve tip and valve seat of the needle valve is made of surfacing cobalt-based hard alloy, which is wear-resistant, sulfur-resistant and erosion-resistant, in line with API Spec 6A specifications, safe and reliable, and has strong interchangeability; Pressure rating is 35/70/105MPa, the working medium is oil and natural gas, the working temperature is -40°C~80°C, the working voltage: DC24V, the material grade EE, the whole travel time: 0s~400s (the speed can be adjusted at 20%~100% in both directions), the communication interface: RS485 (MODBUS-RTU), protection class IP67, explosion-proof class Exdmb II BT6Gb, electrical connection is explosion-proof cable, product power: 90W (maximum) and 1W (standby), output torque is 200N·m (100~350 N·m can be selected). It has the functions of anti-freeze blocking, low pressure and high pressure protection and safety cut-off. It can break ice by impact. The torque + stroke double judgment can ensure that the valve can be fully closed and accurately control the opening scale of the needle valve.

Aiming at the problem that the needle valve is prone to freezing and blocking in production due to throttling and cooling in winter, the ice breaking function through impacting is designed. After the automatic needle valve controller detects the over-torque, the controller does not alarm immediately, but after creeping in the opposite direction for a certain distance, it re-accelerates and continues the original action to break the ice. The parameters such as reverse times, reverse action duration, stop time, and ice breaking times can be set, and the ice breaking effect can be guaranteed with a large torque (the maximum torque of the needle valve is 240N·m). In view of the problem of easy erosion of needle valves, in addition to using wear-resistant, sulfur- resistant and erosion-resistant surfacing cobalt-based hard alloy as the valve tip and valve seat of the needle valve, a filter with a reinforced filter element is added in the design, which fundamentally eliminates the problem of needle valve erosion.

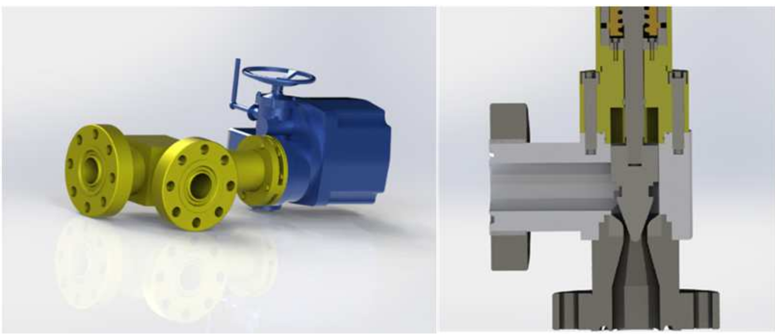

Figure 5. *A diagram of the appearance and its internal structure of remote-controlled automated needle valve.*

3.2. Control System

Another important component is the remote-control automated intermittent production control system, whose schematic diagram is shown in Figure 6. It can fulfill free adjustment of 0~100% opening, with an accuracy of 1‰; it has high pressure and low pressure protection functions, and can set constant pressure adjustment mode by PID; it can realize timing/constant flow/constant pressure control mode, automatically adjusts the opening by the pre-setting time, it realizes the alternate production of multiple wells. The needle valve can also be automatically adjusted for the opening by tracking the pre-designed pressure and gas flow rate; the pressure range of automatically adjusting can be set, the well can be automatically closed under low pressure to restore the pressure, and be opened under high pressure to keep producing; it has real-time data monitoring and rich data analysis functions, real-time production data monitoring provides sufficient data for production adjustment; it has an alarm system, system self-checking alarms, and triple reminders via SMS, WeChat, and email to ensure the safe operation of the system.

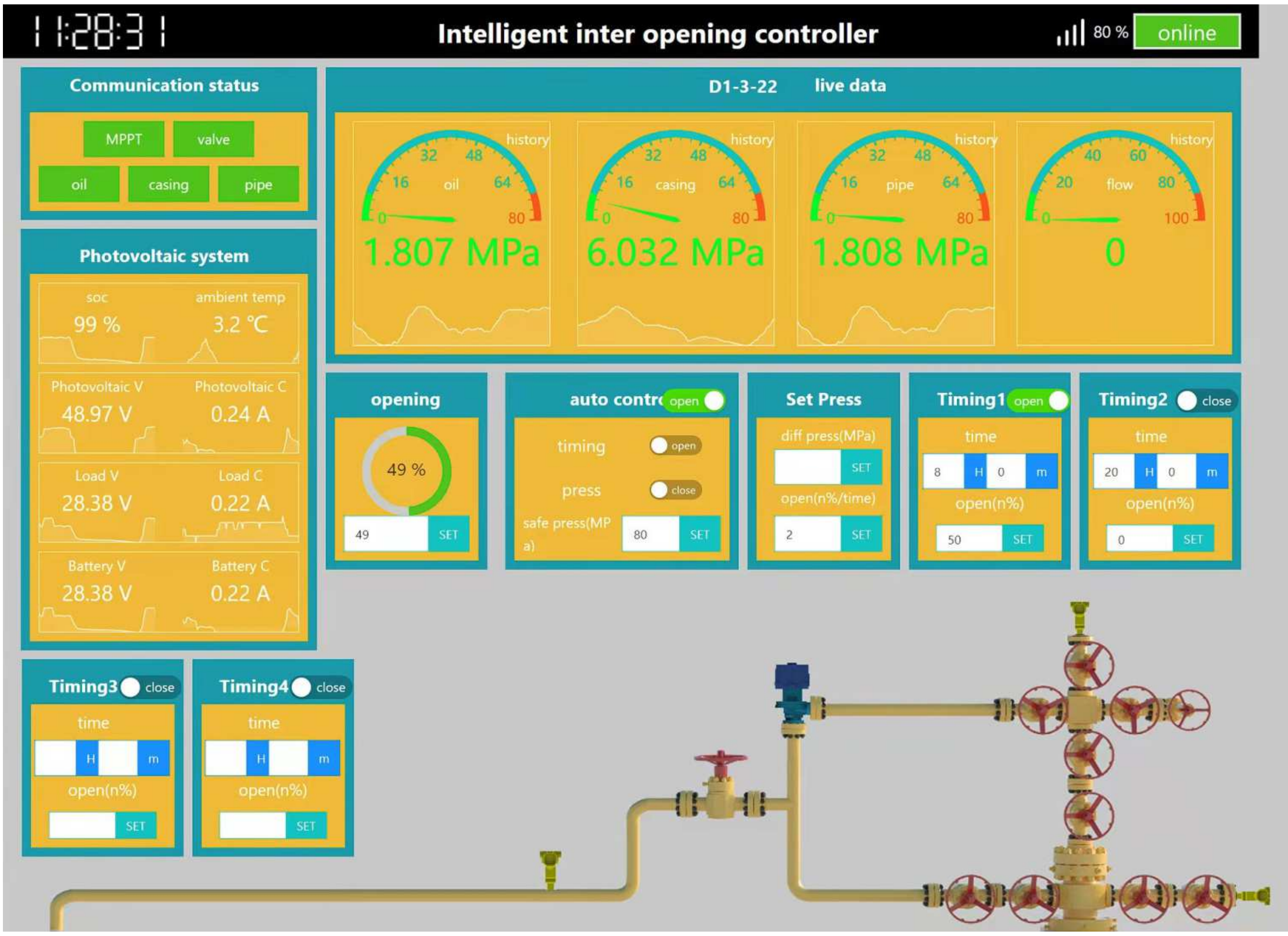

Figure 6. *The remote-control interface of remote-controlled automated needle valve intermittent opening system.*

Other important designs include: the remote-control system adopts redundant dual-channel Modbus control, and the bus communication channel adopts electrical isolation technology; the actuator adopts non-intrusive design, with secondary sealing, and supports infrared remote control and buttons for parameters. It can completely realize the debugging without opening the cover; the ISO5210 standard interface is used between the valve and the actuator; the system will automatically monitor the closing situation, and an alarm will alert the monitoring personnel if there is an internal leakage.

4. Application and Effect Evaluation of Remote-controlled Automated Needle Valve Intermittent Production System

Compared with manual opening and closing wells, the use of the remote-controlled automated needle valve intermittent production system reduces the workload of manual opening and closing (it can avoid the problems of no guarantee for intermittent production and low production time caused by external interference factors such as road conditions, weather, and community issue, etc.). It can also remotely manipulate wells to adjust the production of gas wells, make the gas production rate above the critical liquid-carrying flow rate, and ensure normal liquid-carrying of gas wells to achieve the purpose of stabilizing and increasing production, and reducing the use of foam agent injection can also produce certain economic benefits.

4.1. The Effect Evaluation of Production Increase

Well Y3-4 is a horizontal well in L Well block. It was drilled on August 13, 2016, completed on October 30, 2016. Total measured depth: 4332m (vertical depth 2991.08 m), formation: Permian Shanxi Formation. From September 29, 2017 to October 8, 2017, the Shan2^3 reservoir was fracturing, and then the 88.9mm production string was used for the flowback test, and the "one-point method" was used to calculate the absolute open flow (AOF) of the well Q_{AOF} =

48.8×10^4 m^3 /d [15]. It was put into production in October 2018, and the phenomenon of liquid loading occurred at the end of 2020, requiring frequent intermittent production, and the production time decreased. As shown in Figure 7, the remote-control automated intermittent production needle valve system was installed on May 20, 2021. After the needle valve was installed, the well was remotely controlled to open and close according to production parameters such as gas rate, temperature and pressure, which reduced the ineffective production time and improved the gas well production time. Its gas production also increased accordingly.

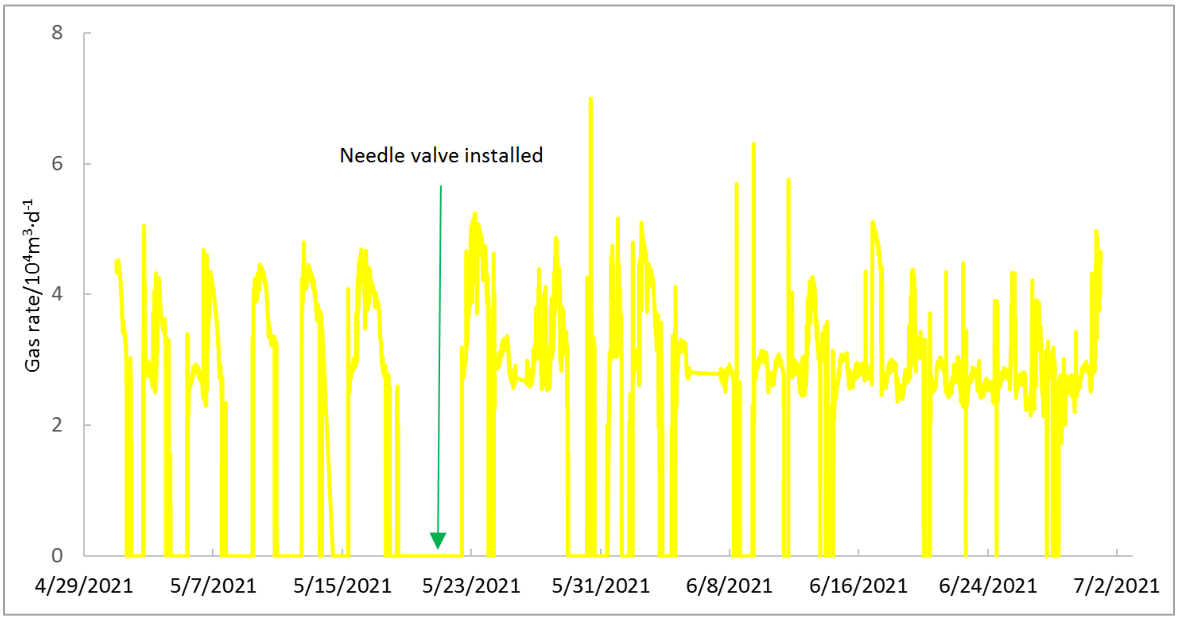

Figure 7. *Gas rate change before and after remote-controlled automated needle valve intermittent opening system.*

A total of 21 wells in L Well block currently use remote-control automated needle valves, which have achieved remarkable effects in increasing and stabilizing production. Taking the 7 wells that were initially installed with these needle valves as an example, gas production increased on different levels. The details are shown in Table 1. It can be seen from the table that the gas rate of 5 wells after the remote-control automated needle valve is installed is higher than before, the estimated average production in January without installation is 1.75×10^4 m^3/d, and the actual average production in January after installation is 1.87×10^4 m^3/d, 6.86% higher than before installation. 2 wells (Y6-2 and Y3-2) encountered production declined issue, the main reason is these 2 wells are installed with 114.3mm (inner diameter 99.6 mm) casing as a production string, while other wells installed with 88.9mm (inner diameter 74.2mm) or 73.02mm (inner diameter 62mm) tubing as a production string, the smaller sized tubing has better liquid unloading capacity than big sized casing. And the opening time of all wells has also increased, and the opening time rate of 7 wells has increased by an average of 5.16%. In general, the gas rate of 71% of the gas wells was stable and increased, and the opening time of 100% of the gas wells increased.

Table 1. *Production data before and after remote-controlled automated needle valve installation.*

Well	Install date	Actual aver. Gas rate in 1 month before/10^4 $m^3 \cdot d^{-1}$	Estimated aver. Gas rate in 1 month after/10^4 $m^3 \cdot d^{-1}$	Actual aver. Gas rate in 1 month after/10^4 $m^3 \cdot d^{-1}$	Increased gas in 6 months/10^4 m^3	Aver. increased prod. time/%
Y3-1	2021/1/10	0.61	0.58	0.71	27.72	1.42
Y5-2	2021/1/12	3.61	3.45	3.95	96.84	1.21
Y3-6	2021/5/20	3.93	3.75	3.95	18.87	2.02
Y3-4	2021/5/21	0.84	0.8	1.09	15.64	23.19
Y5-1	2021/5/22	0.54	0.52	0.56	4.9	4.77
Y6-2	2021/5/23	1.03	0.98	0.87	-12.8	3.43
Y3-2	2021/1/8	2.24	2.14	1.97	-69.27	3.90
Aver.		1.83	1.75	1.87	11.7	5.16

Remarks: The estimated production without needle valve installation is calculated at a monthly decline rate of 4.5%.

As shown in Table 1, 5 wells out of the 7 wells have obvious gas increase, which shows that it has certain economic efficiency. The evaluation time of Y6-2 in the other two wells is one month after installation, which is relatively short; for the other well Y3-2, although its total production increase is -69.27×10^4 m^3, it can be seen from Figure 8 that after continuous optimization for the production regime, its production currently tends to increase and is close to the estimated one, and it is expected that there will be a gas increase in a relatively short period of time in the later period. Even if there is no gas increase, after using the smart needle valve, it is not necessary to frequently go to the field to manually operate the well or inject foam agent, which reduces the risk exposure and carbon emissions of driving, and has good economic benefits on the side.

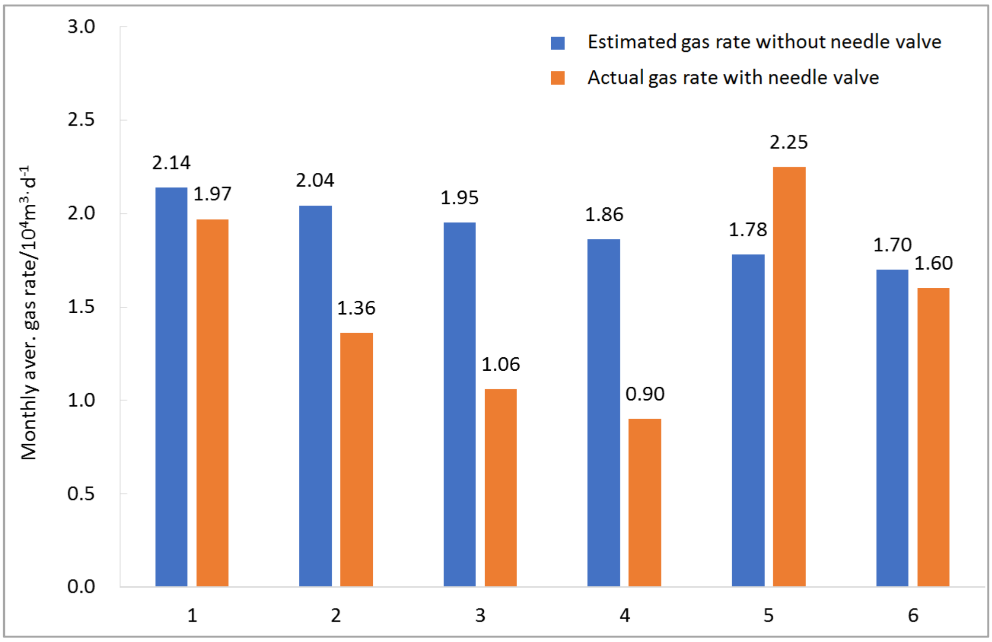

Figure 8. *Gas rate change before and after remote-controlled automated needle valve intermittent opening system.*

4.2. Economic Evaluation

Figure 9 shows the comparison of the times and doses of foam agent injection before and after the installation of the remote-control automated needle valve in Well Y3-4. On the from 13/2/2021 to 18/5/2021, 26 times in 95 days, an average of 1 time in 3 and a half days; after installing the remote-control automated needle valve, from 21/5/ 2021 to 12/8/2021, 6 times in 84 days, an average of 1 time in 14 days. As of June 30, 2021, after the installation of the smart needle valve in Well Y3-4, a total of 20 times of foam agent injection were reduced, and the gas increment within 40 days was 15.64×10^4 m^3. It can be seen that the economic performance of the remote-control automated needle valve system is obviously better.

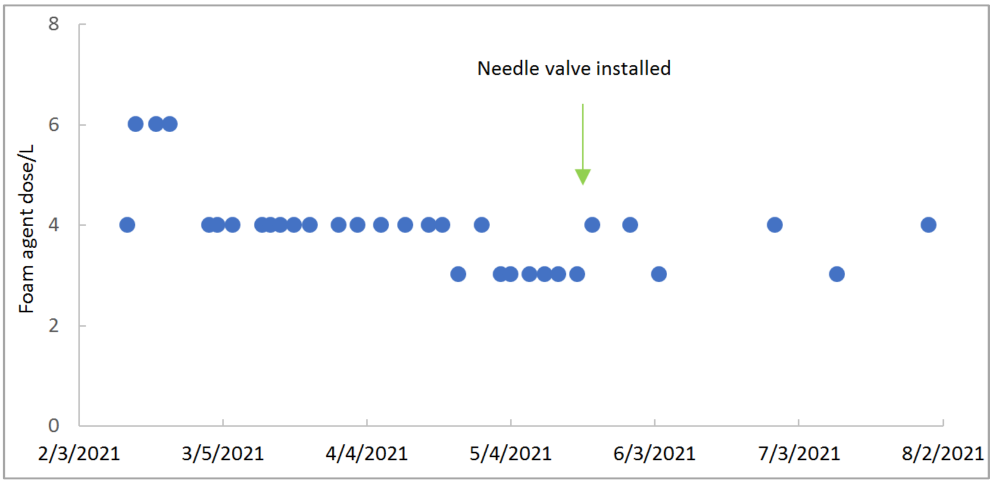

Figure 9. *Comparison of the number and dose of foam drainage before and after the Y3-4 well installation of remote-controlled automated needle valve intermittent opening system.*

5. Conclusion

(1) In view of the problem of frequent opening and closing of liquid-loading gas wells in L Well block, an remote-controlled automated needle valve opening system is designed and developed. The system is easy to install and debug and runs stably. Combined with the use of the digital gas field project, it can be remotely controlled and managed to save human and material

resources. Precisely adjusting the opening of the needle valve can control the flow and open & close wells, which can fully meet the needs of water-produced gas well intermittent production.

(2) Among the 7 wells installed with the remote-controlled automated needle valve system in the L well block, 71% of the gas wells have a stable gas increase, 100% of the gas wells have a higher well opening time, and the liquid loading in the gas wells has been significantly improved. The average gas production increased from 1.75×10^4 m^3/d to 1.87×10^4 m^3/d, which was 6.86% higher than that before installation. The well opening time of 7 wells increased by 5.16% on average.

(3) Regardless of whether it is used as a fixed asset investment or a lease service contract model, compared with manual opening & closing, for researched wells, the comprehensive economic performance of the remote-controlled automated needle valve opening system is excellent.

Nomenclature

CHP = casing head pressure (MPa)
THP = Tubing head pressure (MPa)
Temp. = temperature (°C)
LL = liquid loading (Dimensionless)
AOF = absolute open flow (m^3/d)
IPR = inflow performance relation (Dimensionless)
VLP = Vertical lift performance (Dimensionless)
Pr = reservoir pressure (MPa)

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