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Design and Adaptability Analysis of Integrated Pressurization–Gas Lifting Multifunctional Compressor for Enhanced Shale Gas Production Flexibility

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Abstract: Shale gas development has made significant contributions to the increase in natural gas production capacity in recent years, particularly in promoting the transformation of the energy structure and enhancing energy autonomy. However, with the deepening of shale gas field exploitation, particularly in the later stages of development, low-pressure gas wells and liquid accumulation issues have become increasingly apparent, posing significant challenges to the normal production of gas wells. Traditional single gas lifting and pressurization techniques have disadvantages such as high equipment investment, high operating costs, and inflexibility in switching, which make it difficult to meet the long-term and stable production needs of shale gas fields. Therefore, to overcome these challenges, this study proposes an innovative integrated pressurization–gas lifting multifunctional compressor process, which achieves the "pressurization ↔ gas lifting ↔ pressurization–gas lifting synergy" multi-mode intelligent switching function through modular integration design, resulting in higher production flexibility and efficiency. Adaptability assessments were completed on two typical shale gas platforms, and field test results show that the equipment can achieve stable production increases across all three functional modes. The pressurization mode demonstrates good adaptability in gas processing, efficiently pressurizing and transporting natural gas produced from the platform's wells, meeting the increasing demand for gas export. The gas lifting function of the equipment can effectively address gas wells affected by wellbore or bottom-hole liquid accumulation, improving production conditions. In the synergy mode, the equipment design enables the effective collaboration of pressurization and gas lifting functions. Driven by the same power source, the two functional modules work efficiently together, adapting to complex production conditions where both gas lifting and pressurization for gas export occur simultaneously. The innovative process paradigm developed by this study provides an engineering solution for the entire lifecycle of shale gas field development, characterized by equipment integration and intelligent operation, offering significant economic benefits and promotional value.

Keywords: shale gas development; gas lifting; integrated compressor; multi-condition adaptability

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1. Introduction

1.1. Motivation

Shale gas is a clean and efficient unconventional natural gas, and its development and utilization hold significant economic and environmental importance. Since 2000, the United States has initiated the "shale revolution", leading to rapid growth in shale gas production. China, Canada, and Argentina have followed closely behind, achieving large-scale shale gas development as well. As the development of shale gas continues, the reliability and stability of traditional pressurization systems will face numerous challenges. To address this issue, compressors with dual functions of pressurization and gas lifting, as a new type of composite pressurization equipment, have gradually become an important technology in shale gas development. The dual-function compressor process not only achieves technological innovation but also provides significant improvements in economic efficiency and operational convenience, meeting the modern shale gas development demands for efficiency, sustainability, and low cost. It provides strong technical support for the sustainable development of the shale gas industry.

1.2. Literature Review

The core challenges in shale gas development lie in addressing rapid production decline, dynamic changes in production parameters, and the high costs of surface facilities. In recent years, numerous scholars have conducted extensive research on modular design and mathematical planning methods for shale gas development. Guarnone et al. [1] proposed a modular gathering system to reduce construction costs, while Hong et al. [2] further developed a system framework that simultaneously optimizes production planning and modular facility configuration, addressing production uncertainty by maximizing net present value (NPV). Drouven et al. [3,4] employed mixed-integer nonlinear programming (MINLP) to optimize well locations, pipeline layout, and compression power; Soni et al. [5] and Peng et al. [6], respectively, addressed well drilling-fracturing scheduling and production uncertainty using mixed-integer linear programming (MILP) and multi-stage stochastic programming. These studies indicate that modular design and mathematical modeling can significantly enhance the economic feasibility of development. However, there is limited research on the design of production systems for shale gas platforms, which refer to the integrated surface facilities that collect, process, and transport gas from multiple shale gas wells within a specific development area.

There are two methods for shale gas platform development: pressurization production and gas lifting production. Pressure production refers to the process of reducing the wellhead back pressure through compression equipment and increasing the outlet pressure of the gathering system, thereby increasing the gas flow from the reservoir to the surface and improving the recovery rate. Extensive research has been conducted in the academic community on pressurization production, with compressors being the core device for pressurization production on shale gas platforms. Therefore, conducting research on compressor operation optimization is crucial. Early studies [7,8] optimized fuel consumption at compressor stations using linearization methods; Zagorowska et al. [9] proposed a new operational optimization framework for compressor stations to address the degradation of compressor functionality over time. Zhou et al. [10], in order to optimize the pressurization mode of the shale gas gathering system, developed a mixed-integer nonlinear programming model based on the existing pressurization mode of shale gas fields. This model can determine optimal pressurization locations, operating power, and compressor unit costs. Dynamic modeling of the shale gas pipeline network is also a critical component of pressurization production on shale gas platforms. Liu et al. [11] combined thermodynamic equations and uncertainty analysis to develop a dynamic pipeline

model aimed at minimizing compressor costs. Sanaye and Mahmoudimehr [12] optimized node pressure and compressor layout parameters. Borraz-Sánchez [13], building upon the research of Frimanslund and Haugland [14], proposed a mixed-integer nonlinear programming model and a mathematical programming algorithm based on a global optimizer to solve the operational optimization problem of large-scale natural gas networks under steady-state assumptions. A significant amount of research has been conducted on pressurization production on platforms; however, studies on the design and adaptability analysis of compressors for pressurization production have not been conducted.

Gas lifting production is an artificial lifting technology primarily used to address wellbore liquid accumulation issues caused by insufficient bottom-hole pressure in the later stages of shale gas well production, thereby maintaining or restoring gas well capacity. Extensive research has been conducted by scholars on gas lifting production. The core of gas lifting technology lies in dynamic regulation of multiphase flow in the wellbore, with scholars establishing physical models to reveal gas–liquid flow patterns. Abbasov and Kerimova [15] developed a fluid dynamics model for intermittent gas lifting, addressing the boundary value problem of gas–liquid unsteady flow in the formation-wellbore system. Fan et al. [16], addressing liquid accumulation issues in the later stages of shale gas wells, extracted plunger lifting technology evaluation criteria through the analysis of field production characteristics. Jin et al. [17] developed two artificial neural network-based gas lifting models, grounded in physical principles and data-driven approaches. However, as the operating conditions of shale gas wells become more complex, traditional physical models are increasingly insufficient, necessitating integration with data-driven technologies to enhance adaptability. Miao et al. [18] proposed a plunger motion model with dynamically loose coupling of gas–liquid flow. Ohia et al. [19] built an uncertainty evaluation model incorporating parameters such as gas production rate, oil–water ratio, and pipeline pressure, based on a Mamdani-type two-class fuzzy inference system, addressing the optimization of gas-lift wells in the HYSOL oil field in the Niger Delta, Nigeria. Ribeiro et al. [20], addressing gas lifting optimization for offshore platforms, compared and evaluated five control strategies, including economic nonlinear model predictive control (ENMPC), modified economic model predictive control (EMPC), and static real-time optimizer (ROPA). To improve tool efficiency, scholars have focused on hardware improvements and parameter regulation. Altarabulsi and Waltrich [21] quantified through experiments the effects of silicone thermal expansion, compression, and valve chamber thermal expansion on the set pressure of gas-lift valves, proposing improved calculation methods. Tang et al. [22], addressing the critical need for precise control of gas flow and pressure in multi-gas combination exploitation of natural gas hydrates, innovatively proposed a downhole stratified control tool with a multi-stage throttling structure. However, there has been limited research on the design of dual-function pressurization and gas lifting compressor processes.

The relevant review works of the previous studies are shown in Table 1. In general, there are several shortcomings in the research on the design and adaptability analysis of dual-function pressurization and gas lifting compressor processes for shale gas platforms:

- Current shale gas platform development predominantly adopts either pressurization production or gas lifting production independently, lacking research on the integrated gas lifting and pressurization composite process, which hinders efficient production on shale gas platforms;
- Although some scholars have focused on the development of platform equipment configurations, most of the research is limited to setups for single production modes, resulting in decreased production efficiency;
- Few scholars have conducted adaptability analyses of pressurization and gas lifting systems on platforms.

Table 1. Literature review.

Ref.	Shale Gas Development	Pressurization Production		Gas Lifting Production	
		Device Design	Adaptability Analysis	Device Design	Adaptability Analysis
Guarnone et al. [1]	√				√
Hong et al. [2]	√				√
Zagorowska et al. [9]		√			
Zhou et al. [10]	√		√		√
Liu et al. [11]			√		
Abbasov and Kerimova [15]					
Fan et al. [16]	√				√
Jin et al. [17]	√				√
Altarabulsi and Waltrich [21]				√	
Tang et al. [22]				√	
This paper	√	√	√	√	√

1.3. Research Objectives and Scope

This study addresses the critical challenges faced in shale gas development, particularly the increasing prevalence of low-pressure gas wells and liquid accumulation issues in later exploitation stages. Traditional single-function approaches (either gas lifting or pressurization) present limitations including high equipment investment, substantial operating costs, and operational inflexibility. Our research objective is to develop an innovative integrated solution that overcomes these limitations through a multifunctional compressor process. The scope encompasses the design of a modular system capable of intelligent mode switching between pressurization, gas lifting, and synergistic operations to enhance production flexibility throughout the entire lifecycle of shale gas fields. Our methodology combines theoretical analysis, equipment development, and field validation on typical shale gas platforms to demonstrate adaptability across varying production scenarios and provide a technically viable and economically beneficial engineering solution for the industry.

1.4. Paper Organization

The structure of the article is as follows: Section 2 describes the different processes for shale gas; Section 3 introduces the functions and design of compressors; Section 4 explains the process design of the integrated pressurization–gas lifting unit; Section 5 analyzes application cases of the integrated pressurization–gas lifting unit on two platforms; Section 6 presents the conclusions.

2. Process Description

In recent years, shale gas development has made significant contributions to increasing natural gas production capacity, playing a crucial role in driving energy structure transformation and enhancing energy autonomy. Its unique extraction methods and resource characteristics have injected strong momentum into optimizing the global energy landscape. However, in the later stages of shale gas well extraction, issues such as low-pressure gas wells and liquid accumulation are becoming increasingly prominent. These issues severely disrupt the normal production order of gas wells, significantly restricting the efficient

and stable extraction of shale gas fields, and have become a key bottleneck hindering increased production.

Descriptions of different shale gas processes are shown in Figure 1. To address issues such as pressure decline and liquid accumulation in gas wells, traditional methods use gas lifting and compressor pressurization processes. However, gas lifting and compressor equipment are associated with high investment costs, substantial energy consumption, and ongoing high operational costs. Additionally, their large footprint and lack of flexibility when switching between different operating conditions make it difficult for them to meet the complex, long-term stability requirements of shale gas fields. The integrated technology subfigure presents our novel approach, with a modular compressor system where C1–C5 represent different compressor cylinders with specific functions. C1, C2, and C3 form a three-stage compression system dedicated to gas lifting operations, while C4 and C5 serve as compression cylinders for the pressurization function. All cylinders are connected by a heat exchange tube bundle and driven by a central driving machine, enabling efficient energy utilization across both functions. Given the simultaneous demand for pressurization and gas lifting in shale gas fields, the development of integrated pressurization–gas lifting equipment can effectively improve the flexibility of equipment switching, reduce overall costs, lower carbon emissions, and enhance efficiency.

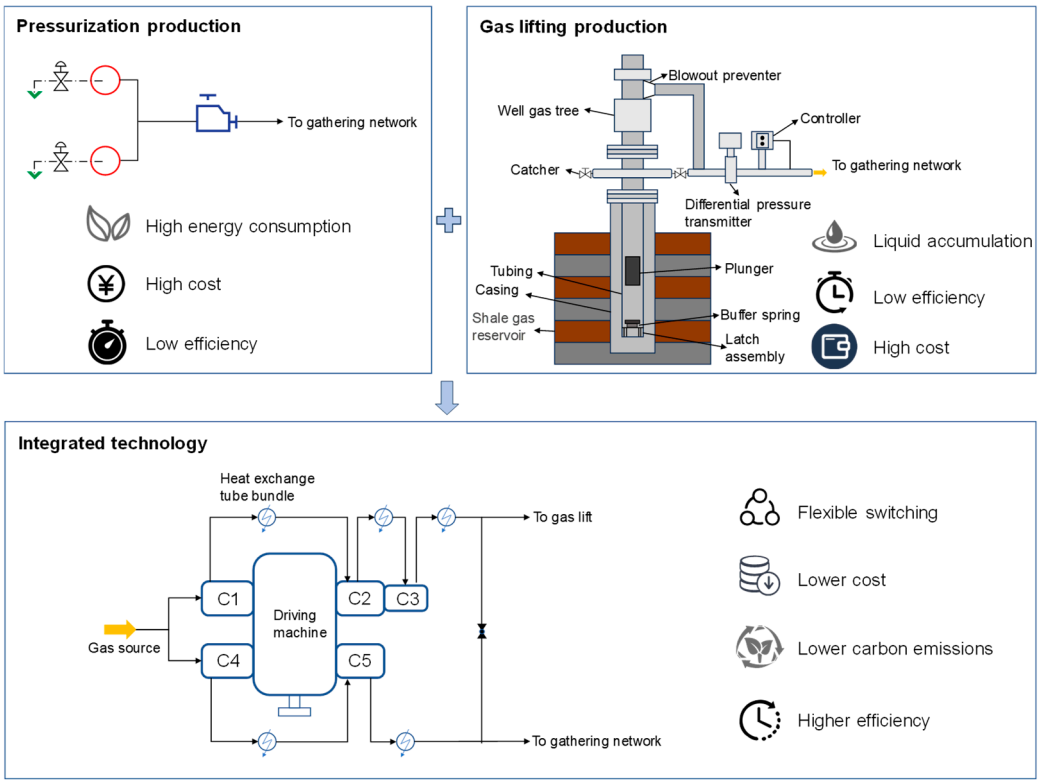


Figure 1. Process description.

3. Compressor

3.1. Operational Characteristics

Gas lifting drainage and pressurization gathering are critical operational measures in oil and gas field development. To reduce the amount of field equipment, improve the standardized management of on-site equipment, lower operational costs, and mitigate environmental and safety risks, while also meeting the process requirements for 24 h continuous gas lifting and pressurization gathering operations, this study has designed and developed an integrated compressor unit.

The integrated compressor unit is a fully functional, highly integrated gas compression device, primarily consisting of a natural gas compressor skid, a box-type substation, supporting cables, process pipelines and valves, and a metering system. In terms of pressure parameters, its intake pressure range is 0.3–1.5 MPa, capable of meeting the gas compression requirements under various gas source pressure conditions. The maximum gathering pressure reaches 2.5 MPa, suitable for conventional gas gathering processes; in gas lifting operations, the maximum gas lifting pressure can reach up to 25.0 MPa, demonstrating the ability to output high-pressure gas. In terms of main unit operating parameters, the speed remains stable at 985 r/min, ensuring high efficiency and stability during the gas compression process. The gas lifting compression is designed with three stages, progressively increasing gas pressure through multistage compression to meet the stringent requirements for high-pressure gas in gas lifting operations, while gathering compression is designed with two stages, effectively facilitating gas collection and transportation. In terms of power, the main motor has a power output of 500 kW, providing strong support for the entire compressor unit and ensuring stable equipment operation. The cooling system employs mixed cooling technology, combining the advantages of multiple cooling methods to effectively reduce heat generated during the compression process, ensuring that the equipment maintains good thermal stability while operating efficiently.

3.2. Function

The integrated compressor unit designed in this study is shown in Figure 2. This integrated pressurization–gas lifting equipment incorporates advanced pressure-regulating valves, with an intake pressure range of 0.3–1.5 MPa. For specific platforms, when gas well capacity is insufficient, this equipment can use the production network as a gas source, enabling the "pressurization + gas lifting" composite function. The equipment uses a single power source to drive the compressor, efficiently extracting and pressurizing gas from the wellhead, reducing the wellhead pressure to below 1 MPa. The gas source from the tubing of all gas wells on the platform is connected to the compressor's intake. After two stages of pressurization, the pressure can reach up to 6 MPa. The pressurized gas is then split into two parts: one part is fed into the export pipeline, while the other part, according to the platform's well demands, undergoes three-stage compression, increasing the pressure to 15–35 MPa. This gas is then injected into the platform's gas lifting casing, entering the annulus of the wells requiring gas lifting to discharge wellbore liquid and assist in gas well production. Each gas injection line of the wells is equipped with a gas flow control valve and flow meter. When a well requires gas lifting, the gas injection conduit and gas injection volume can be adjusted by precisely regulating the wellhead tree valve switch and the throttle valve opening of the injection line, enabling gas lifting without requiring shutdown. The coordination between the "one machine, multiple lifts" and the alternating gas lifting pipeline process ensures that the gas lifting function covers all gas wells on the platform.

(1) Gas Lifting Function

The natural gas, after being separated in the first-stage separator, serves as the gas source for the gas lifting section. The gas lifting section is equipped with three compression cylinders, which compress the natural gas in stages. After each stage of compression, the gas passes through an air cooler to reduce its temperature, ensuring the efficiency and safety of the compression process. The natural gas, after three stages of compression, is connected to the wellhead gas lifting pipeline, thereby enabling the gas lifting function of the well and effectively enhancing its production efficiency.

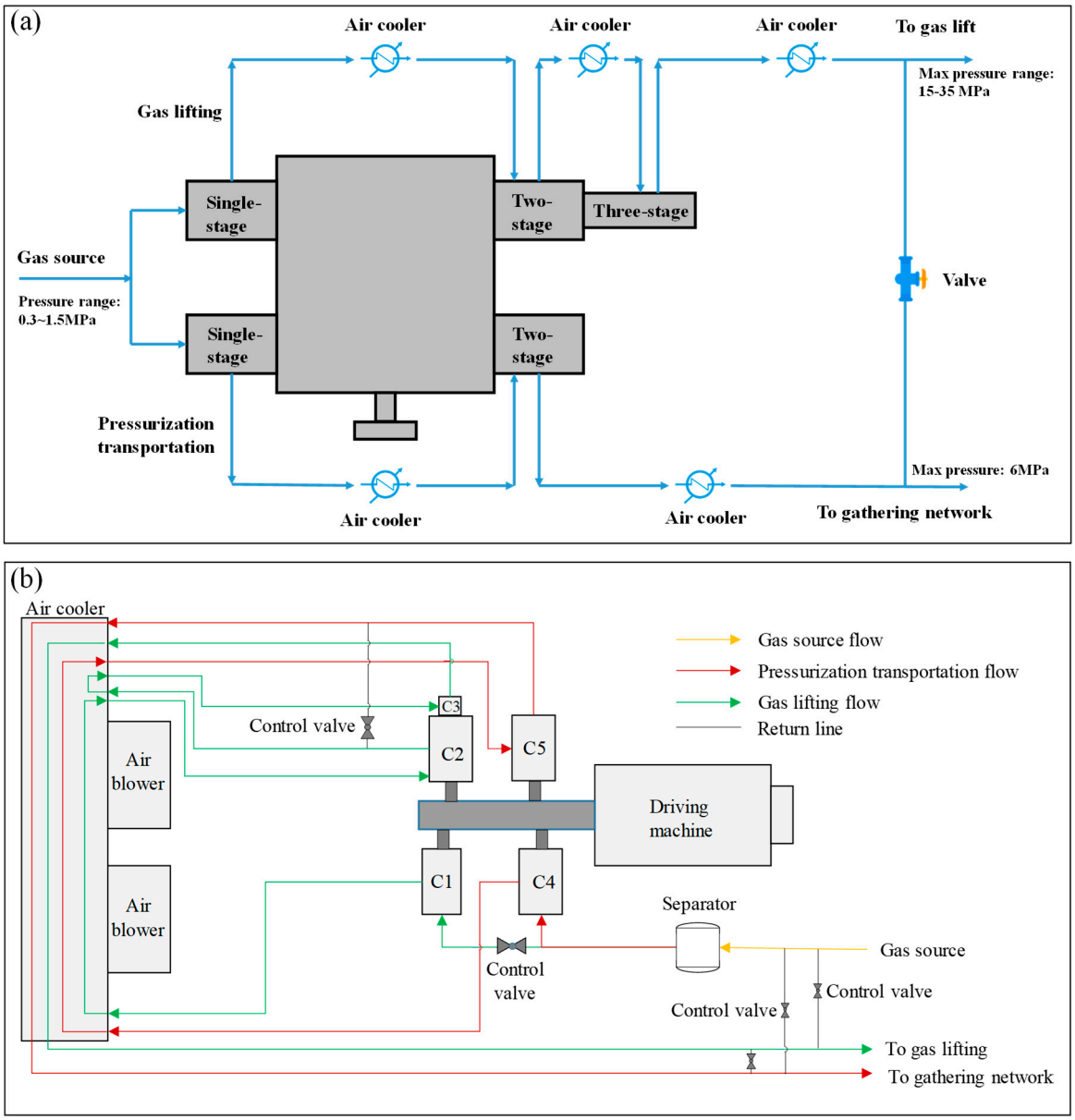


Figure 2. Compressor unit process flow: (**a**) simplified; (**b**) detailed.

(2) Pressurization function

Pressurization and gas lifting share a common intake pipeline, with a pressure-regulating valve installed on the pipeline to ensure stable gas pressure, providing a continuous stable gas source to the compressor intake separator. After separation in the separator, natural gas enters the compression cylinders for two-stage compression, and the compressed gas is then transported to the downstream central station. During each compression stage, the gas passes through an air cooler to reduce its temperature, ensuring that the gas temperature meets the transportation requirements. When only a single compression stage is required, the switching position of the relevant blind plates can be reversed to connect the first and second-stage compression cylinders, allowing the compressed gas to be cooled and then delivered to the downstream central station. Additionally, a bypass pipeline is installed on the export pipeline. When the pressure in the gas lifting section is insufficient, the bypass line can be used for supplementary pressurization. Meanwhile, safety valves are installed between the intake separator and the first and second-stage

compression cylinders to effectively prevent equipment from operating under excessive pressure, ensuring safe and stable operation.

(3) Pressurization and gas lifting function

As shown in Figure 2b, the natural gas, after being separated in the first-stage separator, simultaneously provides a gas source for both the gas lifting and pressurization sections. The gas source for the gas lifting section directly enters the subsequent gas lifting compression process; the pressurization section relies on an intake pipeline equipped with a pressure-regulating valve to supply gas to the compressor intake separator while maintaining stable gas pressure. The gas lifting section compresses the natural gas in stages using three compression cylinders (labeled as C1, C2, and C3 in Figure 2b). After each compression stage, the gas is cooled in an air cooler. After three stages of compression, the gas is routed to the wellhead gas lifting pipeline, enabling the gas lifting function. The natural gas for the pressurization section, after separation in the intake separator, enters the compression cylinders (labeled as C4 and C5 in Figure 2b) for two-stage compression (in special cases, only a single compression stage may be conducted by reversing the blind plate switch position, connecting the first and second-stage compression cylinders). After each compression stage, the gas is cooled in an air cooler, and the cooled compressed gas is then transported to the downstream central station. A bypass pipeline is installed on the export pipeline. When the pressure in the gas lifting section is insufficient, the export gas from the pressurization section can be used for supplementary pressurization. Additionally, safety valves installed between the intake separator and the first- and second-stage compression cylinders ensure that the equipment will not operate under excessive pressure when both gas lifting and pressurization are running simultaneously, ensuring the safe and stable operation of the entire system.

4. Methodology

The integrated pressurization–gas lifting unit proposed in this study utilizes an innovative process design, achieving the seamless integration of pressurization and gas lifting functions. The equipment, through a rational gas flow design and control system, can flexibly switch operating modes under various working conditions. To make the process flow easier to observe and understand, the subsequent description will omit the heat exchange processes between stages, focusing solely on the flow direction of natural gas between the equipment stages, as shown in Figure 3. This simplified diagram is intended solely to aid in understanding the flow principles and does not represent the actual complete process flow.

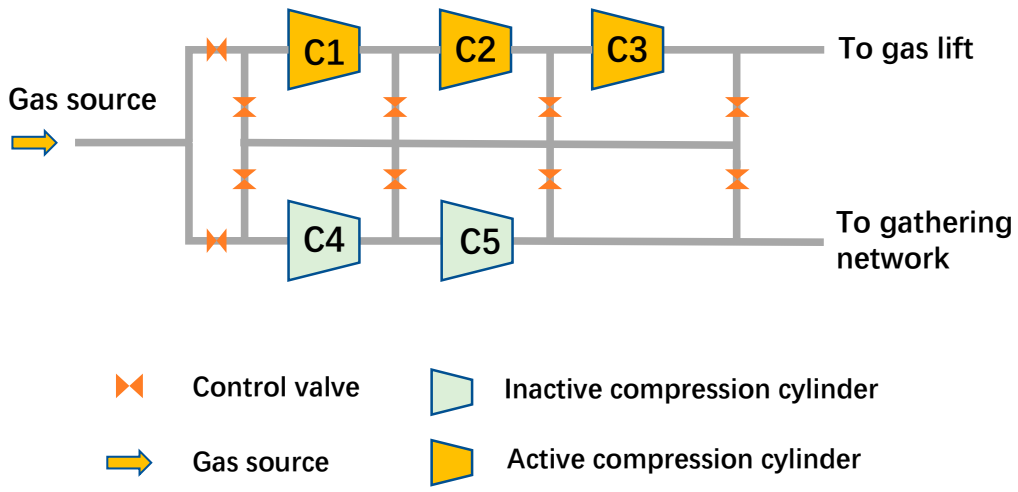


Figure 3. Process structure of the integrated pressurization–gas lifting dual-function compressor.

(1) Gas lifting process

The gas flow in the gas lifting process is shown in Figure 4. The gas lifting section utilizes a three-stage compression process, with natural gas separated in the first-stage separator providing the gas source for the gas lifting section. The gas undergoes three stages of compression, with each stage followed by cooling through an air cooler, ultimately achieving the injection of high-pressure gas into the annulus of the target well for gas lifting and liquid removal. The system can either use wellhead gas as the gas source or utilize pipeline gas as a supplementary source, providing strong adaptability to different gas sources, as shown in Figure 4a. The gas injection volume can be precisely adjusted to meet the varying needs of different gas wells. When higher injection pressure is required, the system can use the natural gas pressurized by the second-stage compression cylinders as the gas source and further increase the gas lifting outlet pressure by applying secondary energy loading from the third-stage compression cylinder group, as shown in Figure 4b.

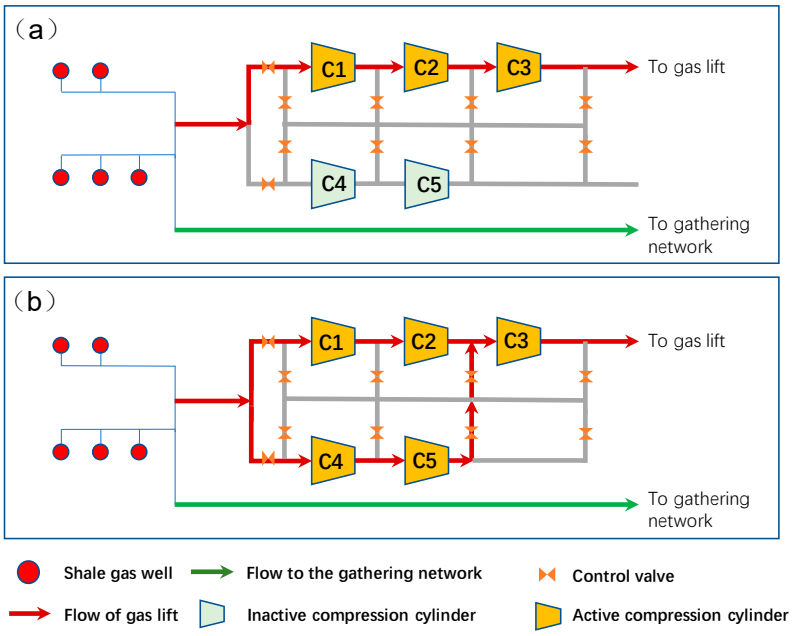


Figure 4. Gas lifting process flow: (**a**) scenario 1; (**b**) scenario 2.

(2) Pressurization process

The pressurization section employs a two-stage compression process and shares the intake pipeline with the gas lifting section. A pressure-regulating valve is installed on the intake pipeline to ensure stable intake pressure. After separation in the separator, natural gas enters the compression cylinders for two-stage compression, with the gas being cooled by an air cooler after each stage of compression. When only a single compression stage is required (i.e., in situations with lower pressure ratio demands), as shown in Figure 5a, the system employs a mechanical device similar to an automobile clutch to control the connection state between each compression stage and the drive shaft. Although all compression stages are physically connected to the same drive shaft, through this 'clutch mechanism', it is possible to control whether each compression stage actually participates in the work. For example, when it is necessary to suspend the compression function of the second-stage cylinder, the 'clutch mechanism' puts that cylinder in a stopped state, allowing gas to still pass through the compression cylinder without being compressed, with the cylinder effectively functioning as a bypass pipeline. This design allows the system to flexibly adjust its working state according to actual requirements, achieving functional diversity while maintaining a compact structure. The system is equipped with

comprehensive safety protection devices to ensure the safe and stable operation of the equipment. The system can flexibly adjust the process flow for different pressurization scenarios: When the platform contains both high-pressure and low-pressure shale gas wells, the high-pressure gas well can directly feed into the gathering network without pressurization, while the low-pressure gas well can feed into the gathering network through one or two stages of compression and pressurization, as shown in Figure 5a,b. Under large gas flow conditions, parallel gas lifting cylinders can also be used as a supplementary pressurization, enhancing the overall pressurization export capacity of the system, as shown in Figure 5c.

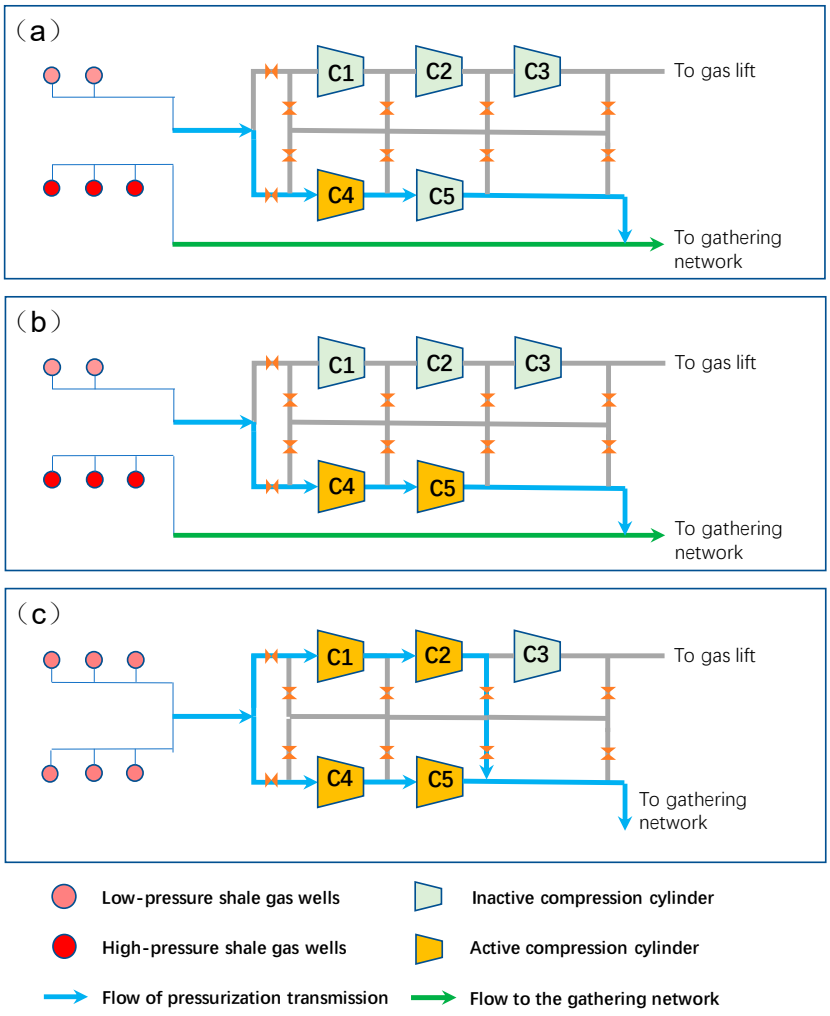


Figure 5. Pressurization process flow: (**a**) scenario 1; (**b**) scenario 2; (**c**) scenario 3.

(3) Pressurization and gas lifting process

The final step is the coordinated operation of gas lifting and pressurization functions. Through a well-designed gas flow system, the equipment can provide a stable gas source for gas lifting while ensuring pressurization export. After being distributed, the natural gas entering the compressor is split, with one portion entering the pressurization process for export and the other portion entering the gas lifting process for wellbore liquid removal. The two functions can seamlessly switch between each other, and the operating mode can be flexibly adjusted according to the working conditions without requiring a shutdown. In the coordinated operation mode, the system can dynamically adjust the ratio of pressurization to gas lifting based on real-time production data from the platform. When a well requires an increased gas lifting volume, the pressurization export volume can be appropriately

reduced; conversely, when the export pressure is insufficient, the gas lifting volume can be decreased to ensure the export demand is met. Part of the gas at the pressurization transmission outlet can also be diverted to the C3 compression cylinder inlet for greater gas lift injection, as shown in Figure 6.

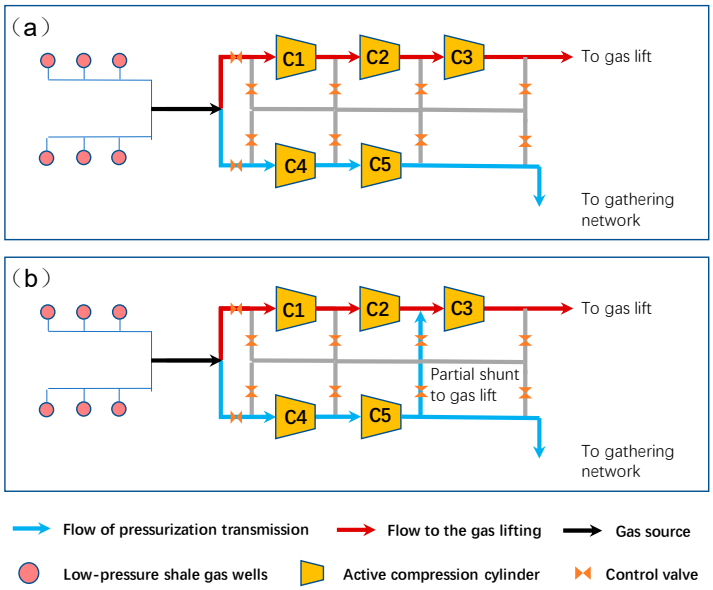


Figure 6. Pressurization and gas lifting process flow: (**a**) scenario 1; (**b**) scenario 2.

In summary, the integrated design offers significant advantages over traditional single-function equipment. Firstly, it reduces the number of devices, lowering investment and operational costs; secondly, it improves equipment utilization efficiency; and thirdly, it enables flexible switching of functions, better adapting to the diverse needs throughout the entire gas field development process.

5. Case Studies

5.1. Case Description

This study conducts an adaptability analysis of the integrated pressurization–gas lifting multifunctional compressor through field trials on two typical shale gas platforms, H1 and H2, located in southwest China. All data presented in this section were collected from actual field measurements using calibrated industrial sensors installed on the operational equipment. The platforms are subjected to three production regimes—gas lifting, pressurization, and pressurization–gas lifting—with each regime implemented for a period of 10 days. The integrated pressurization–gas lifting multifunctional compressor was physically installed on both platforms according to the design described in previous sections, with comprehensive instrumentation for real-time data collection. Before the introduction of the integrated pressurization–gas lifting multifunctional compressor, gas wells on both the H1 and H2 platforms were experiencing varying degrees of interference due to wellbore or bottom-hole liquid accumulation, which had severely affected the normal production of the wells.

5.2. Case 1

Before the introduction of the integrated pressurization–gas lifting multifunctional compressor, the H1 platform had a daily average gas production of 2.08×10^4 m^3 (April average), with an average casing pressure of 5.83 MPa, average oil pressure of 2.32 MPa, and average export pressure of 1.76 MPa. All three gas wells on the H1 platform were expe-

riencing interference from wellbore or bottom-hole liquid accumulation, which severely affected the normal production of the wells. Therefore, on 4 June 2024, the H1 platform introduced the integrated pressurization–gas lifting equipment, began installation operations, and resumed normal production, with the goal of restoring well capacity and increasing recovery rates. A three-phase trial was conducted on the H1 platform, as shown in Figure 7. The first phase involved gas lifting on wells H1-1, H1-2, and H1-3 for a total of 10 days; the second phase involved pressurization on wells H1-1, H1-2, and H1-3 for 20 days; and the third phase involved both pressurization and gas lifting on wells H1-1, H1-2, and H1-3 for 10 days.

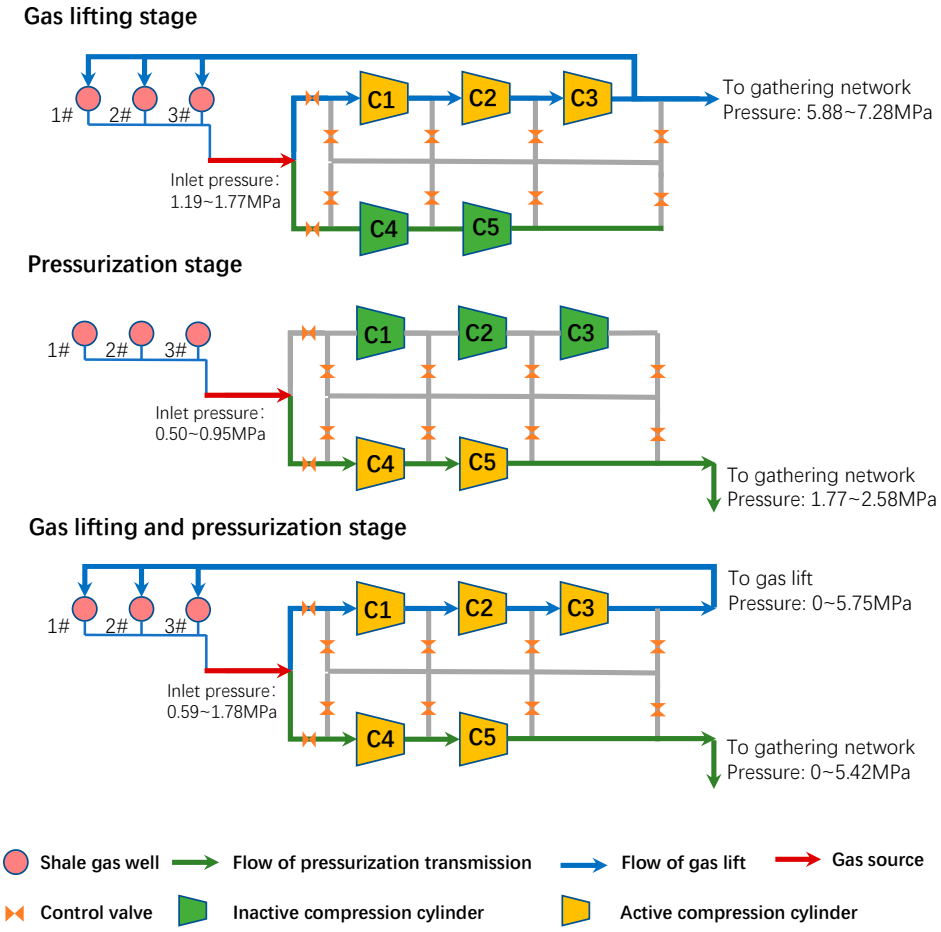


Figure 7. Three-phase test schematic of the H1 platform.

(1) Gas lifting production adaptability analysis

The gas well production data during the gas lifting phase are shown in Figure 8. On the H1 platform, gas lifting was simultaneously conducted on wells H1-1, H1-2, and H1-3 for a total of 10 days. The intake pressure on the H1 platform ranged from 1.19 to 1.77 MPa, and the gas lifting discharge pressure ranged from 5.88 to 7.28 MPa. The total increased production ranged from 2.15 to 6.65 $\times$ 10^4 m^3/d, with an average increase of 4.14 $\times$ 10^4 m^3/d. The exported gas volume ranged from 1.49 to 4.98 $\times$ 10^4 m^3/d, with an average export volume of 2.66 $\times$ 10^4 m^3/d. The difference between the pressurization volume and export volume represents the gas injection volume for gas lifting. By implementing alternating gas lifting injection (i.e., cyclically switching gas injection among wells H1-1, H1-2, and H1-3 based on real-time downhole pressure and production monitoring), the system was able to meet the varying needs of different gas wells on the platform, demonstrating excellent process adaptability. This sequential approach allows for optimal allocation of gas

resources and avoids the need for simultaneous gas lifting of all wells, which would require significantly higher injection volumes.

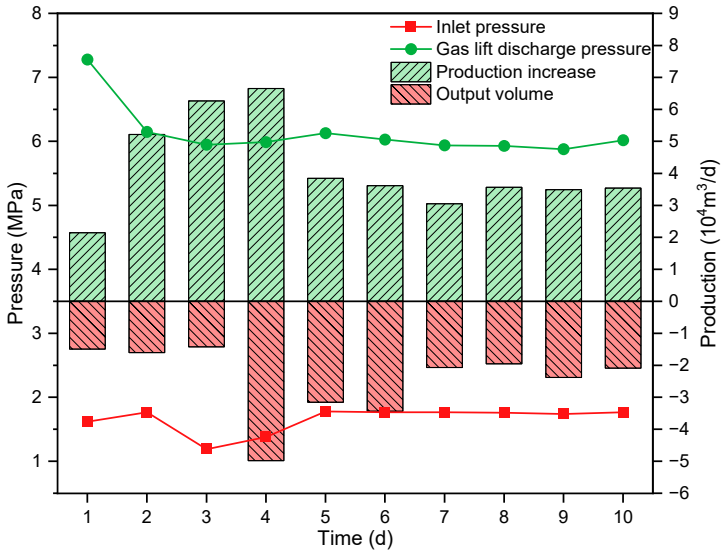


Figure 8. Gas lifting phase gas well production data.

(2) Pressurization production adaptability analysis

The gas well production data during the pressurization phase is shown in Figure 9. During this phase, the three wells on the H1 platform underwent two stages of pressurization for a total of 10 days. From the data, it can be observed that the intake pressure on the H1 platform ranged from 0.5 to 0.95 MPa, and the pressurization discharge pressure ranged from 1.77 to 2.58 MPa. The total increased production ranged from 2.14 to 3.52 $\times$ 10^4 m^3/d, with an average increase of 2.81 $\times$ 10^4 m^3/d. This indicates that the pressurization function of the equipment exhibits good adaptability in gas volume handling. The equipment's maximum discharge pressure is designed to be 4 MPa, and it can stably output pressure according to downstream pipeline requirements, providing reliable support for transporting natural gas to the central station. The pressure regulation range meets the platform's production needs.

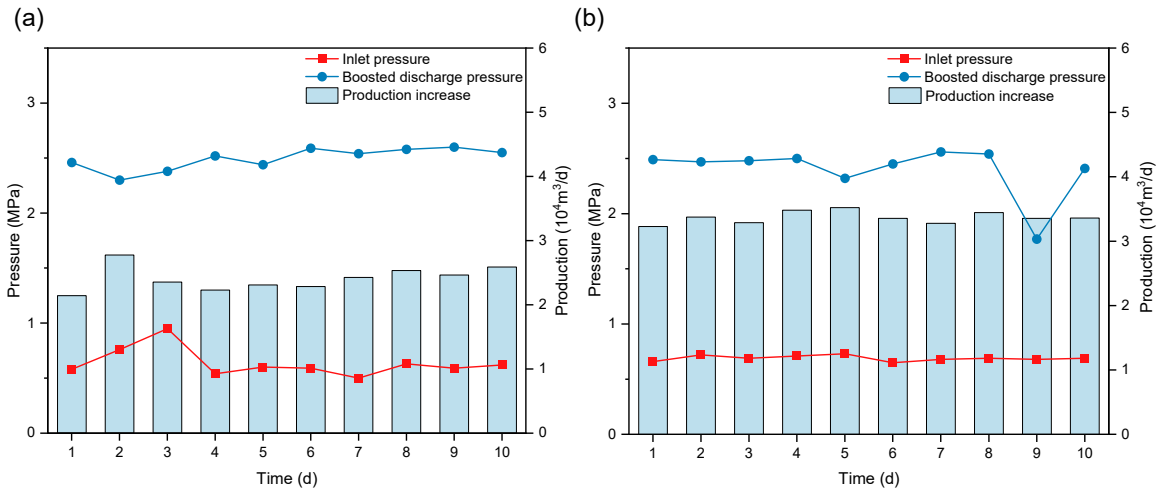


Figure 9. Pressurization phase gas well production data: (**a**) stage 1; (**b**) stage 2.

(3) Pressurization and gas lifting production adaptability analysis

The gas well production data during the pressurization and gas lifting phase is shown in Figure 10. During this phase, the H1 platform conducted pressurization and gas lifting on wells H1-1, H1-2, and H1-3 for a total of 10 days. From Days 1 to 3, the integrated pressurization–gas lifting equipment pressurized wells H1-1, H1-2, and H1-3, and gas lifted wells H1-2 and H1-3; from Days 4 to 10, the equipment pressurized H1-1, H1-2, and H1-3, and gas lifted well H1-1. The intake pressure on the H1 platform ranged from 0.59 to 1.78 MPa, the pressurization discharge pressure ranged from 0 to 5.42 MPa, and the gas lifting discharge pressure ranged from 0 to 5.75 MPa. The average increased production was 5.28 × 10^4 m^3/d, with an average gas injection volume of 2.48 × 10^4 m^3/d and an average export volume of 2.33 × 10^4 m^3/d. During the simultaneous operation of both functions, the system effectively ensured stable production from the platform's gas wells, significantly improving the overall production stability of the platform and meeting its long-term production needs.

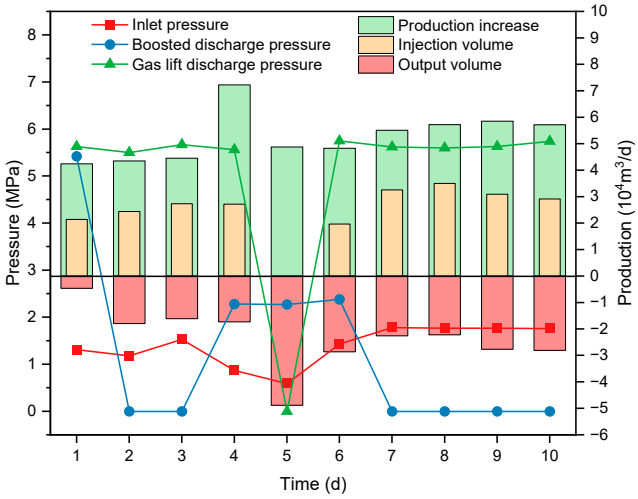


Figure 10. Pressurization and gas lifting phase gas well production data.

(4) Compressor analysis

The compressor pressure at different production stages is shown in Table 2. By analyzing the inlet and output pressures of the compressor, it can be observed that the pressurization and gas lift stage allows for flexible operation within a wide range of inlet pressures, while providing a higher output pressure compared to the pressurization stage. The integrated compressor enables the system to more effectively handle low-pressure gas source conditions while maintaining good output performance. Furthermore, compared to the gas lift stage, it also has lower energy consumption. Therefore, the integrated compressor offers significant advantages in improving production efficiency and optimizing resource utilization, making it especially suitable for production environments that require flexibility and adaptability.

Table 2. Compressor pressure.

Production Stage	Inlet Pressure (MPa)	Output Pressure (MPa)
Normal	1.74~1.78	1.74~1.78
Gas lift	1.19~1.77	5.88~7.28
Pressurization	0.50~1.10	1.77~2.58
Pressurization and gas lift	0.59~1.78	2.27~5.42

(5) Economic analysis

The costs and revenues for platform H1 are shown in Figure 11. The average energy consumption of the gas lift production compressor is 1670 kW, with an average net present value of 7.91 × 10^4 CNY. In contrast, the average energy consumption of the booster production compressor is 1240 kW, with an average net present value of 5.53 × 10^4 CNY. Due to the integrated compressor's dual functionality, which enables both boosting and gas lifting operations, the energy consumption for boosting gas lift production is the highest, with the average production increase also being the greatest. As a result, the average gas sales revenue and net present value for boosting gas lift production surpass those of the separate boosting and gas lift operations, amounting to 9.20 × 10^4 CNY and 9.07 × 10^4 CNY, respectively.

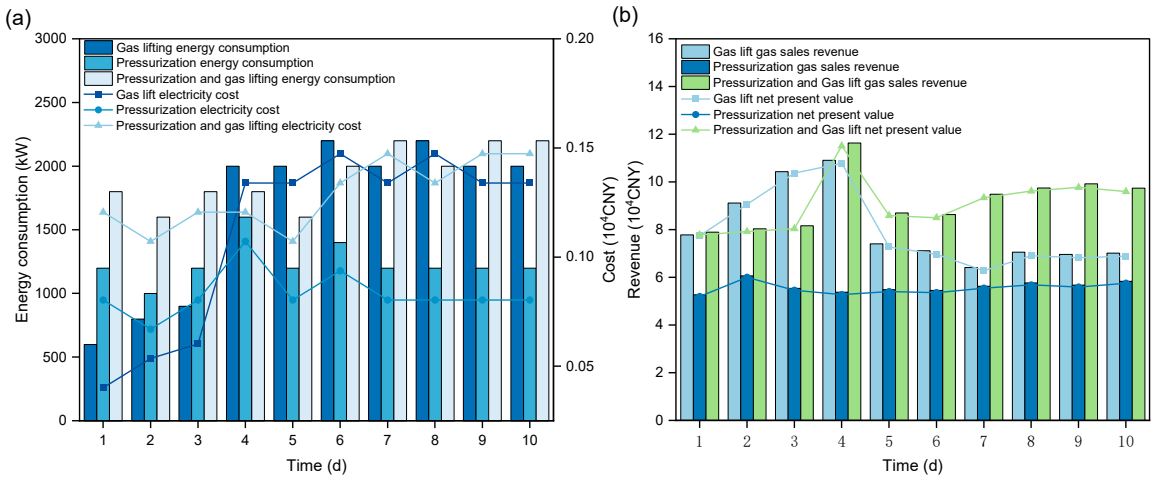


Figure 11. Costs and revenues stages for platform H1: (**a**) energy consumption and costs; (**b**) revenue.

5.3. Case 2

The H2 platform was commissioned in mid-June 2022, with the initial test volume from three gas wells reaching 64.2 × 10^4 m^3. By the end of July 2024, the platform primarily relied on continuous small-scale pressurization and stage-based truck-mounted gas lifting to maintain production. At that time, the daily average gas production was 2.3 × 10^4 m^3 (July average), with an average casing pressure of 4.04 MPa, average oil pressure of 0.55 MPa, and average export pressure of 1.73 MPa. Due to varying degrees of wellbore or bottom-hole liquid accumulation interference in all three gas wells, the normal production of the gas wells was severely impacted. Against this backdrop, on August 1, 2024, the H2 platform introduced integrated pressurization–gas lifting equipment, and installation operations were carried out. The equipment was officially put into normal production on September 4, with the aim of resolving the gas well production issues and improving production efficiency. The adaptability analysis of the pressurization and gas lifting functions of this equipment on the platform is of significant importance. Two-phase trials were conducted on the H2 platform. In the first phase, pressurization was performed on wells H2-1, H2-2, and H2-3, while gas lifting was conducted on well 2, with a total of 15 days of testing. In the first phase, the average daily gas production was 6.4 × 10^4 m^3, with 2.7 × 10^4 m^3 of gas reinjected into well 2, and 3.7 × 10^4 m^3 exported. The average daily increase in production was 1.4 × 10^4 m^3. In the second phase, pressurization and gas lifting were carried out on wells H2-1, H2-2, and H2-3 for a total of 40 days, as shown in Figure 12.

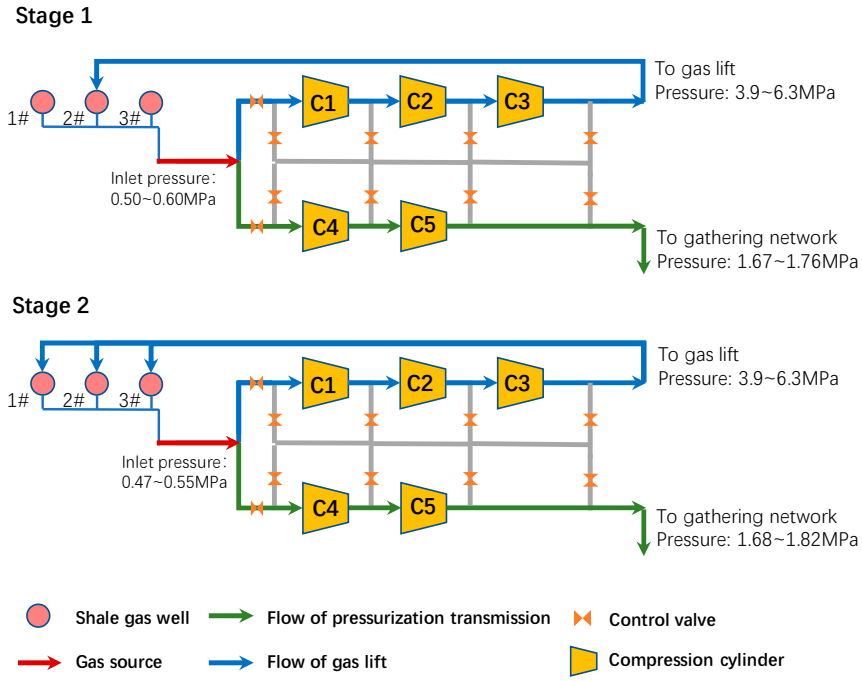


Figure 12. Two-phase test schematic of the H2 platform.

(1) Gas lifting production adaptability analysis

The gas lifting section of the integrated pressurization–gas lifting equipment uses natural gas separated by the first-stage separator as the gas source shown in Figure 13. The intake pressure range is 0.3–1.5 MPa, and in the actual operation of the H2 platform, the average intake pressure was 0.53 MPa (with a maximum of 0.60 MPa), which is fully within the equipment's designed intake pressure range, indicating that the gas source pressure conditions are well-suited. Additionally, the design using the production network as a supplementary gas source provides an effective way to supplement the gas source when the well capacity is insufficient, enhancing the adaptability of the gas lifting function under varying gas source conditions.

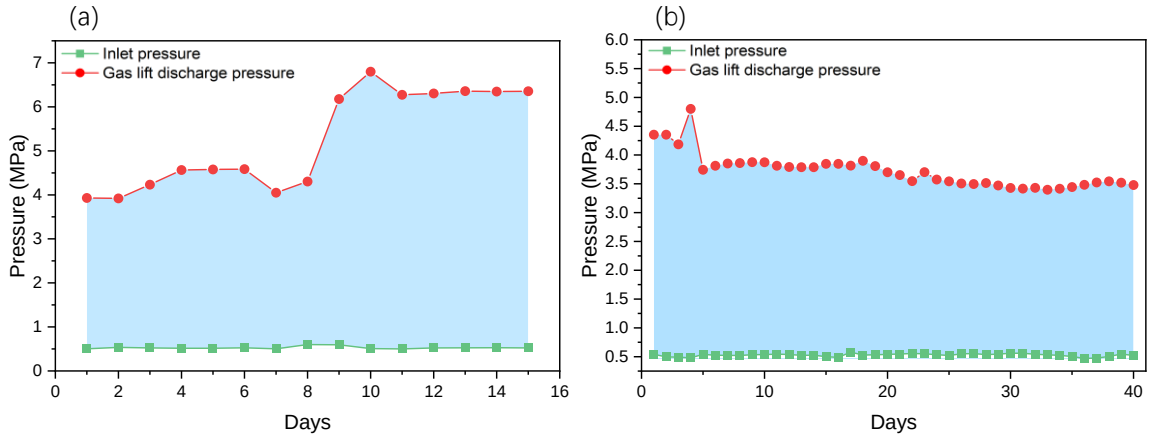


Figure 13. Gas lifting phase inlet and outlet pressure: (**a**) stage 1; (**b**) stage 2.

Regarding gas injection volume, as shown in Figure 14, the average gas injection volume for well 2 during the first phase was 2.58 × 10^4 m^3/d. In the second phase, operating in the "one machine, three lifts" mode, the total daily average gas injection volume for the three wells was 3.13 × 10^4 m^3/d. By installing gas flow control valves and flow meters on the gas injection lines of each well, the gas injection conduit and gas

injection volume can be flexibly adjusted without the need for shutdown. This is achieved by adjusting the wellhead tree valve switches and throttle valve openings on the gas injection pipelines, allowing for alternating gas lifting. This method meets the varying gas lifting needs of different wells on the platform, demonstrating excellent process adaptability.

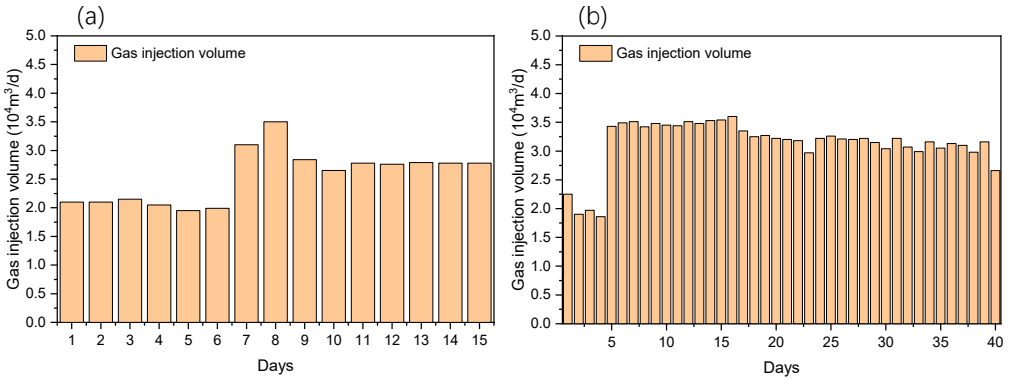


Figure 14. Gas lifting injection volume: (**a**) stage 1; (**b**) stage 2.

(2) Pressurization production adaptability analysis

Pressurization function adaptability tests were conducted. During the testing period, significant changes in gas well production data were observed. Compared to the previous 2.3×10^4 m^3/d, stable increased production was achieved, as shown in Figure 15. According to the data, after the pressurization section was activated on the H2 platform, the average intake pressure was 0.52 MPa (with a minimum of 0.3 MPa), which was lower than the previous wellhead oil pressure. This indicates that the equipment can effectively adapt to lower intake pressure conditions, expanding the applicable range of gas source pressures. The maximum discharge pressure of the equipment is designed to be 4 MPa, and the actual average discharge pressure during operation was 1.73 MPa, which can stably output pressure based on downstream pipeline requirements, providing reliable support for transporting natural gas to the central station. The pressure regulation range meets the platform's production needs.

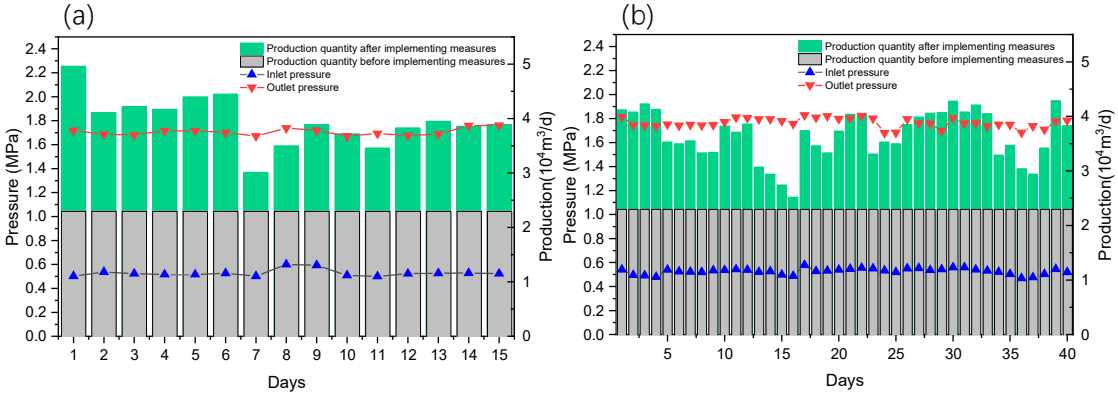


Figure 15. Pressurization adaptability analysis: (**a**) stage 1; (**b**) stage 2.

After implementing the integrated pressurization–gas lifting process on the platform, the average total export gas volume reached 3.73×10^4 m^3/d. Compared to the pre-operation total export gas volume of only 2.3×10^4 m^3/d, the daily increase in production was 1.43×10^4 m^3, with a significant increase in pressurization gas volume. This strongly demonstrates that the pressurization function of the equipment is well-suited for gas

volume handling, efficiently pressurizing and transporting the natural gas produced by the platform's gas wells, meeting the platform's growing production export gas demand.

The pressurization system is equipped with safety valves installed between the intake separator and the first and second-stage compression cylinders, effectively preventing the equipment from operating under excessive pressure, ensuring the safe and stable operation of the equipment under various operating conditions. A bypass pipeline is installed on the export pipeline, allowing for supplementary pressurization when the pressure in the gas lifting section is insufficient, further enhancing the system's ability to handle complex operating conditions. This improves the adaptability and reliability of the pressurization function in the platform's production process.

(3) Pressurization and gas lifting production adaptability analysis

The H2 platform is currently operating with simultaneous pressurization and gas lifting (one machine, three lifts) modes. Through gas lifting flow testing, the maximum gas lifting flow rate can reach 5.5×10^4 m^3/d without affecting pressurization, fully meeting the demand for simultaneous gas lifting on all three wells. This indicates that the equipment design achieves good coordination between the pressurization and gas lifting functions. Under a single power source, both functional modules work efficiently together, adapting to the platform's complex production conditions of gas lifting and liquid removal, as well as pressurization export.

During the simultaneous operation of both functions, the gas lifting effect is evident, while also ensuring stable production from the platform's gas wells. The average total export gas volume reached 3.7×10^4 m^3/d, as shown in Figure 16. This demonstrates that the dual-function pressurization and gas lifting mode can effectively enhance the overall production stability of the platform, meeting the long-term, stable production requirements of the platform, and providing reliable technical support for efficient shale gas extraction and transportation.

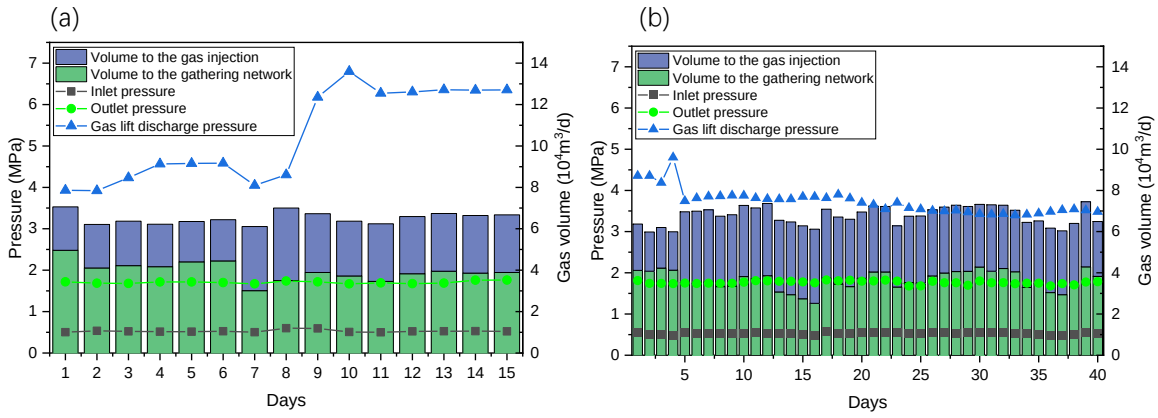


Figure 16. Pressurization and gas lifting adaptability analysis: (**a**) stage 1; (**b**) stage 2.

(4) Economic analysis

The energy consumption and net present value for platform H2 are shown in Figure 17. The average energy consumption of the compressor in stage 1 is 8165 kW, with an average net present value of 7.42×10^4 CNY. In stage 2, the average energy consumption of the compressor is 8290 kW, with an average net present value of 7.91×10^4 CNY. In stage 2, the dual-function operation of the integrated compressor increases energy consumption but effectively improves the overall net present value.

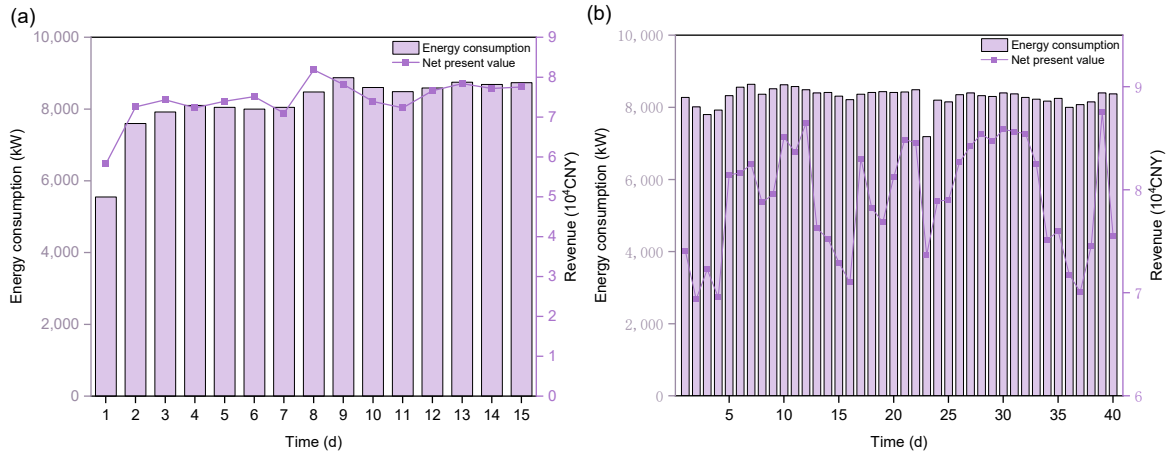


Figure 17. Energy consumption and net present value for platform H2: (**a**) stage 1; (**b**) stage 2.

6. Conclusions

The integrated pressurization–gas lifting multifunctional compressor process proposed in this study, through an innovative modular integration design, achieves flexible switching between gas lifting, pressurization, and coordinated operation modes, effectively addressing the issues of low-pressure gas wells and liquid accumulation faced by shale gas platforms. Through application research on typical shale gas platforms, the equipment has demonstrated significant advantages in improving production efficiency, reducing operational costs, and lowering equipment investment. The specific conclusions are as follows:

(1) This study successfully developed an integrated pressurization–gas lifting dual-function compressor, which enhances the equipment's adaptability and flexibility under different operating conditions by optimizing the gas flow design and control strategies, meeting complex production demands. The equipment can flexibly switch operational modes based on the platform's actual needs, ensuring efficient and stable operation.

(2) The integrated compressor unit enhances gas lift operation efficiency through multi-stage compression and high-pressure gas output, effectively addressing the issue of liquid accumulation and ensuring stable production. The high-power motor of the compressor ensures an efficient and stable gas compression process, boosting production capacity, promoting the long-term stable exploitation of oil and gas fields, and maintaining a high recovery rate.

(3) By combining the gas lifting and pressurization functions, this process effectively increases gas well production and resolves issues related to low pressure and liquid accumulation. Field test results indicate that under gas lifting mode, the equipment significantly improves the production conditions of gas wells; under pressurization mode, the equipment stably outputs the required pressure, ensuring continuous production on the platform.

(4) The integrated compressor unit design reduces the number of devices, lowers construction and maintenance costs, and improves energy utilization efficiency. At the same time, the equipment shows significant advantages in reducing carbon emissions, providing strong support for the sustainable development of shale gas fields.

(5) The process and equipment solutions proposed in this study can be widely applied to various shale gas platforms, particularly in multi-well joint extraction and complex gas source development environments. The new equipment not only meets the demands of shale gas development across its entire lifecycle but also provides technical assurance for efficient development and long-term operation. In conclusion,

the integrated pressurization–gas lifting dual-function compressor process offers an innovative, economical, and environmentally friendly solution for shale gas extraction, playing an important role in enhancing shale gas field production efficiency, reducing operational costs, and driving energy structure transformation. It has significant practical implications and broad application prospects.

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Conflicts of Interest: Authors Kunyi Wu, Lin Qu, Yan He, Yu Wu and Chenqian Zhang were employed by the company Research Institute of Gathering and Transportation Engineering Technology, PetroChina Southwest Oil & Gas Field Company. The remaining 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.

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