

Development and Experimental Verification of a 1m³ Explosion-Proof Electro-Hydraulic Sand Mixing Skid for Coal Mine Underground Hydraulic Fracturing

Zeyuan Li¹, Jinjian Yu², Xintang Liu², Congliang Xu², Ruikun Pang¹

¹ CRRC Qingdao Sifang Rolling Stock Research Institute Co., Ltd., Qingdao 266031, China

² Qingdao Hongpu Technology Co., Ltd., Qingdao 266031, China

Abstract

To address the demand for efficient and safe sand mixing equipment in hydraulic fracturing operations within coal mine underground environments, this paper presents the development of a 1m³ electro-hydraulic driven sand mixing skid. The equipment adopts an electro-hydraulic drive system, adapting to the explosion-proof requirements of coal mine underground settings. It integrates key modules including a hydraulic system, electrical control system, and mechanical structure. The paper elaborates on the development background, technical specifications, working principles, and overall system design (covering mechanical structure, hydraulic system, and electrical control system), as well as the prototype manufacturing and experimental verification process. Test results demonstrate that the system achieves a discharge flow rate $\geq 1 \text{ m}^3/\text{min}$, a maximum discharge pressure $\geq 0.5 \text{ MPa}$, and a controllable sand concentration range of 3% to 15%, meeting the design requirements. During an 8-hour full-load temperature rise test, the hydraulic system exhibited a temperature rise $\leq 50^\circ\text{C}$ while operating stably. The successful development of this equipment provides reliable technical support for hydraulic fracturing operations in coal mine underground environments and holds promising prospects for broader application.

Keywords

Underground Coal Mine; Electro-Hydraulic Driven Sand Mixing Skid; Hydraulic Fracturing; Explosion-Proof Design; Load-Sensitive System.

1. Introduction

Hydraulic fracturing technology in underground coal mines is critical for enhancing coal seam permeability and improving gas extraction efficiency. As core equipment, sand mixing skids directly impact fracturing effectiveness and operational safety^[1]. Currently, underground sand mixing equipment faces challenges such as high energy consumption, complex operation, and insufficient explosion-proof performance, failing to meet modern mining efficiency and safety requirements^[2]. With advancements in intelligent and green mining, higher demands have been placed on equipment reliability, environmental sustainability, and automation^[7-8]. Electro-hydraulic drive systems offer advantages such as high power transmission efficiency, precise control, and ease of explosion-proof design, making them increasingly popular in mining applications^[3-6].

Considering the harsh underground environment (high humidity, dust, and explosive gases) ^[9-11], the development of a 1m³ electro-hydraulic sand mixing skid aims to address the adaptability, energy efficiency, and control precision shortcomings of traditional equipment, providing superior performance for hydraulic fracturing operations.

2. Working Principle

The core working principle involves energy conversion from electrical → hydraulic → mechanical to achieve accurate mixing and transportation of sand, water, and chemical additives:

(1) Power Input: An explosion-proof motor (75kW) connects to underground 660V/1140V dual-voltage power, driving a piston pump to convert electrical energy into hydraulic pressure.

(2) Material Transport & Mixing:

Water is pumped into the mixing tank via a hydraulic motor-driven suction pump (22 ml/r).

Quartz sand is transported by a screw conveyor (80 ml/r), adjustable for 3%–15% concentration.

Chemical additives are injected via a cam rotor pump (50 ml/r) at ≥ 50 L/min.

A mixer (390 ml/r hydraulic motor, 96 rpm) ensures homogenous slurry.

(3) Slurry Output: The discharge pump (44 ml/r) pressurizes slurry to ≥ 0.5 MPa for fracturing.

(4) Intelligent Control: PLC monitors flow, pressure, and temperature, dynamically adjusting motor speeds via a load-sensing hydraulic system.

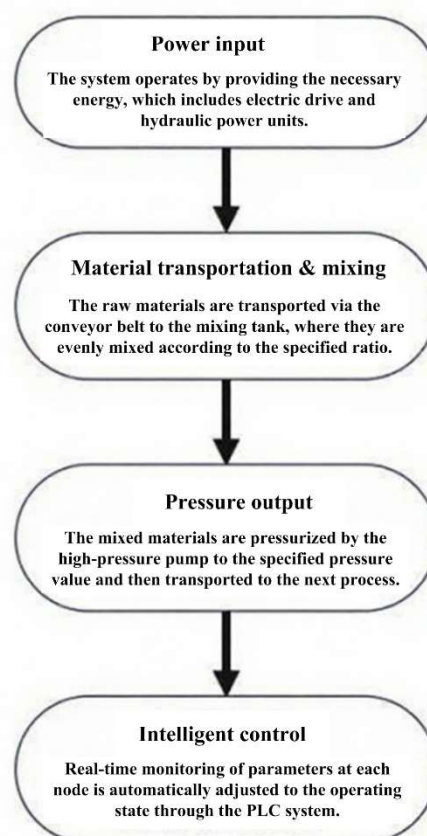


Fig. 1 Schematic of sand mixing skid workflow

3. System Design

3.1. Key Specifications

The equipment adopts an "electro-hydraulic" drive architecture, utilizing explosion-proof motors as the power source to actuate various executive components (including suction pumps, discharge pumps, sand conveying augers, mixers, etc.) through hydraulic systems. This design minimizes direct exposure of electrical components, thereby enhancing explosion-proof safety.

Based on customer-provided design input specifications (Table 1), a comprehensive system design was developed for the sand mixing skid. This integrated solution combines three major modules-mechanical structure, hydraulic transmission, and electrical control-to achieve precise proportioning and homogeneous mixing and delivery of sand, water, and chemical additives.

Table 1. Main Technical Parameters of Sand Mixing Skid

No.	Parameter Item	Parameter Item
1	Discharge flow rate	$\geq 1\text{m}^3/\text{min}$ (adjustable)
2	Maximum discharge pressure	$\geq 0.5\text{MPa}$
3	Mixing tank capacity	0.8m^3
4	Sand concentration control range	3%~15% (adjustable)
5	Chemical additive flow rate	$\geq 50\text{L}/\text{min}$ (adjustable)
6	Maximum overall dimensions	$\leq 4500 \times 1500 \times 1800\text{mm}$
7	Input voltage	660V/1140V (dual-voltage compatible)
8	Total power consumption	$\leq 75\text{kW}$
9	Discharge flow rate	$\geq 1\text{m}^3/\text{min}$ (adjustable)

3.2. Hydraulic System

The hydraulic system adopts load-sensing control technology^[12-13] to achieve on-demand oil supply, effectively reducing energy consumption. The system primarily consists of the following components:

(1) Power Source

A 75 kW explosion-proof motor drives an ER147 piston pump. At 1450 rpm, the pump delivers a maximum flow of 202.5 L/min and reaches 31 MPa working pressure, meeting varying load requirements.

(2) Actuators

Hydraulic motors power critical functions. Suction pump motor (22 ml/r), Discharge pump motor (44 ml/r), Sand conveyor auger motor (80 ml/r), Agitator motor (390 ml/r), Chemical additive pump motor (50 ml/r). Each motor's displacement is optimized for specific operational demands.

(3) Control System

Features a load-sensing proportional valve (TMFPSV55-3-5EA2E1) for independent flow/pressure regulation across actuators.

The main relief valve is set at 28 MPa to ensure system safety and prevent overloads.

Table 2. Key Parameters of the Hydraulic System

No.	Hydraulic Circuit	Motor Displacement (ml/rev)	Flow Rate (L/min)	Working Pressure (MPa)
1	Suction System	22	23.2	16.4
2	Discharge System	44	67.2	22.6
3	Sand Conveyor System	80	32.4	3.9
4	Agitator System	390	39.4	17.6
5	Chemical Additive System	50	22.4	6.3

3.3. Electrical Control Logic

The electrical system is designed in accordance with the explosion-proof requirements for underground coal mines. It mainly includes:

(1) Explosion-proof motor: A YBK3-2805-4 type explosion-proof three-phase asynchronous motor for underground coal mines is selected, with a power of 75kW. It has heating function and a PT100 temperature monitoring probe, and is suitable for the high-humidity environment in the mine.

(2) Control box: A KXJ-250/1140 (660) mine-used explosion-proof and intrinsically safe electrical control box is adopted. It integrates Siemens PLC and MCGS touch screen. Through the upper computer program, it realizes the monitoring of equipment operation parameters and the issuance of control instructions.

(3) Sensors: Explosion-proof electromagnetic flowmeters (inlet and outlet), pressure sensors, temperature sensors, level meters, etc. are configured. They collect real-time system operation data and transmit it via analog signals to the control box.

(4) Protection functions: It has protection functions such as motor overload, over-temperature, and hydraulic system overpressure to ensure the safe operation of the equipment.

3.3.1. PLC Control Logic

The hydraulic system of the sand mixing truck is controlled by PLC (Programmable Logic Controller). The core lies in leveraging the logical operation, timing control, and signal processing capabilities of PLC to precisely regulate the motor start-stop, hydraulic valve actions, and the movement of the actuating components in the hydraulic system, while ensuring the safe and stable operation of the system. The control logic can be decomposed into five core steps: "Signal Acquisition → Logical Operation → Instruction Output → Execution Feedback → Safety Protection".

(1) Signal Acquisition: PLC communicates with the hydraulic system and sensors of the sand mixing truck through analog input module (AI) and digital input module (DI). Such data includes the liquid level of the mixing tank, the rotational speed and output of the stirring shaft, and the pressure of the input pipeline, providing raw data support for subsequent calculations.

(2) Logical Operation: PLC performs multi-dimensional logical operations on the real-time signals collected, conducting process logic, action timing, and abnormal judgment operations. For example, when the motor temperature exceeds the normal range, an abnormal identification logic is automatically triggered, providing a triggering signal for the safety protection section.

(3) Output Instruction: PLC converts the decision results into executable control instructions through digital output module (DO) and analog output module (AO), sending on-off digital instructions to the motor to control start-stop and state switching, and sending analog instructions to the hydraulic valves, outputting a 4-20mA current to precisely adjust the movement speed of the actuating components.

(4) Execution Feedback: After receiving the output instructions from PLC, the motors, multi-way valves, etc. complete the corresponding actions. Meanwhile, the system transmits the actual status after execution back to PLC through the feedback sensors in the signal acquisition section, achieving closed-loop control.

Safety Protection: When the signal acquisition section detects abnormal signals (such as excessive liquid level in the mixing tank, pressing of the emergency stop button), or the logic operation section identifies system faults (such as motor overload, actuating component jamming), PLC immediately triggers the safety protection logic.

3.3.2. Upper Computer Program

The touch screen program of the upper computer includes communication configuration, command issuance, and data acquisition functions. Through the Modbus protocol of the frequency converter and the frequency converter, communication is established. Based on the communication address, as well as the data type and format corresponding to the

communication address, the motor start, motor stop, and input frequency instructions are set. Through Ethernet communication with the programmable logic controller, the real-time transmission of signals such as temperature, speed, and flow rate read from the relevant addresses is sent to the touch screen.

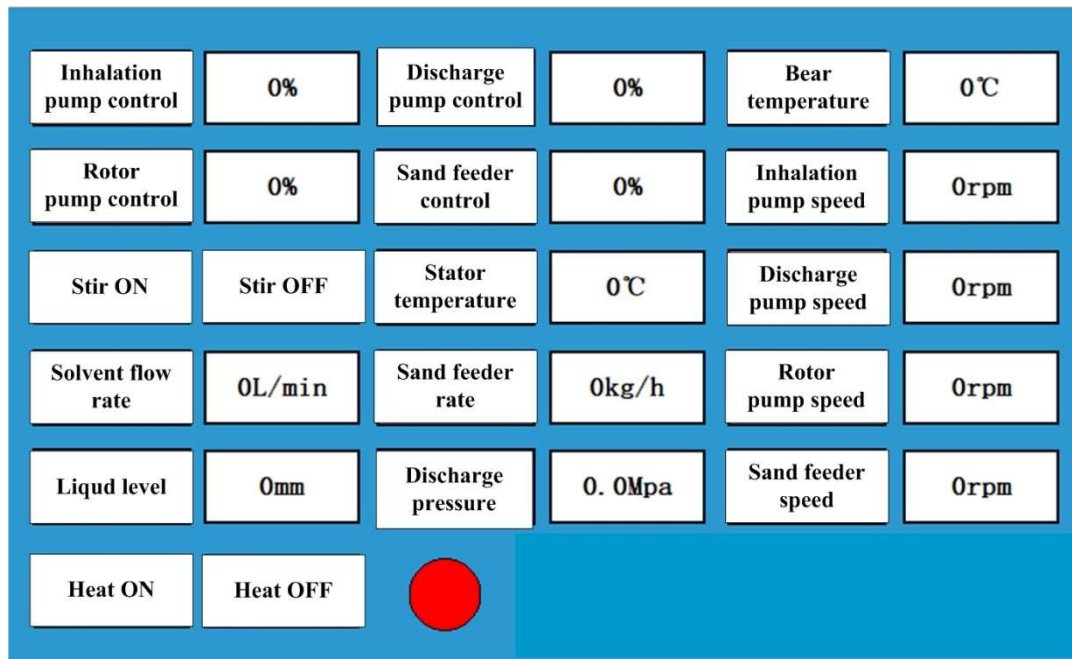
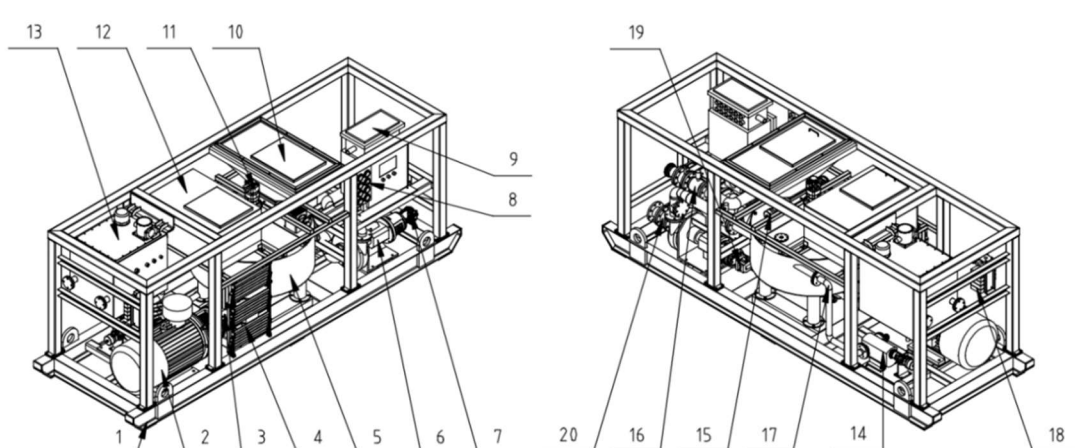


Fig. 2 Touchscreen Control Interface

3.4. Mechanical System

The mechanical design of the entire system includes a hydraulic oil tank, liquid filling tank, frame, sand conveyor, explosion-proof control cabinet, explosion-proof motor, sand mixing and stirring tank, water pipe manifold, and centrifugal pump set, etc. The specific details are shown in Fig. 3.



1. Skid frame 2. Flameproof three-phase asynchronous motor 3. Hydraulic piston pump 4. Handrail ladder 5. Sand mixing and stirring tank 6. Centrifugal pump 7. Piston motor 8. Pressure gauge 9. Flameproof and intrinsically safe electrical control box 10. Sand conveying pipe and screw conveyor 11. Hydraulic cycloidal motor for stirrer 12. Liquid filling tank 13. Hydraulic oil tank 14. Cam rotor pump 15. Cycloidal motor 16. Electromagnetic flowmeter 17. Manifold system 18. Load sensing multi-way proportional directional control valve.

Fig. 3 Mechanical System of the Entire Sand Mixing Skid

The mechanical structure adopts a skid-mounted design, mainly consisting of the following key components:

- 1) Skid frame: Made of high-quality carbon structural steel, with an upper and lower separable structure, facilitating installation and maintenance. The overall size is controlled within 4500×1500×1800mm.
- 2) Mixing tank: With a volume of 0.8 m³, made of austenitic stainless steel, featuring corrosion resistance and wear resistance. An internal stirring impeller is installed to ensure uniform material mixing.
- 3) Sand conveying device: With a spiral auger structure, the impeller material is 16Mn wear-resistant steel, enhancing the conveying capacity and service life of quartz sand.
- 4) Pump mounting base: Used to fix hydraulic actuators such as the suction pump and discharge pump, featuring a vibration reduction design to reduce operating noise.

4. Prototype Development and Test Verification

4.1. Prototype Development Process

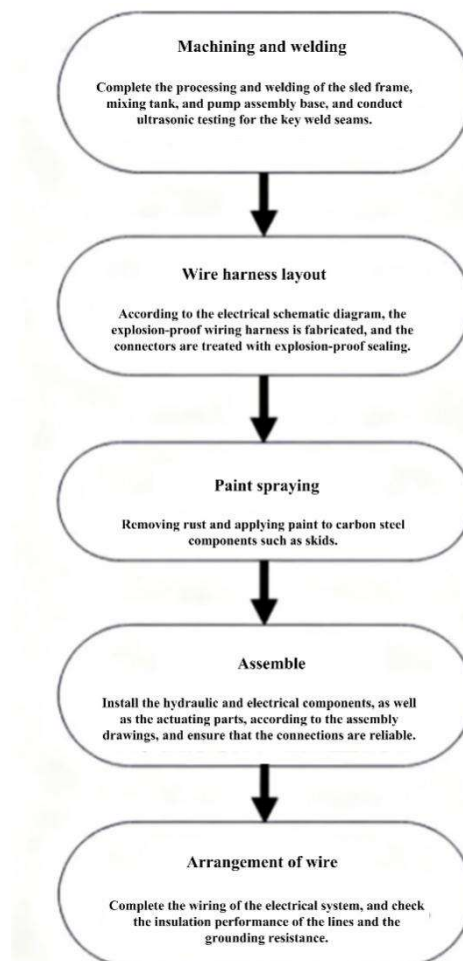


Fig. 4 Prototype Manufacturing Process Flow Chart

The prototype development follows the following process:

- 1) Machining and Welding: Complete the machining and welding of structural components such as the skid frame, mixing tank, pump mounting base, etc. Critical weld seams undergo flaw detection.

- 2) Wiring Layout: Produce explosion-proof wiring according to the electrical schematic. Connectors are treated with explosion-proof sealing.
- 3) Painting: Remove rust and apply paint to carbon steel components such as the skid frame.
- 4) Assembly: Install hydraulic components, electrical components, and actuating parts in sequence according to the assembly drawings to ensure reliable connections of all components.
- 5) Wiring: Complete the wiring of the electrical system and check the insulation performance and grounding resistance of the lines.

4.2. Test Verification

To verify the performance of the equipment, the following tests were conducted:



Fig. 5 Physical diagram of the sand-mixing sled prototype

- 1) Sand discharge test: Within the sand discharge concentration range of 3% to 15%, the stability of the equipment's sand discharge was tested. The results showed that the deviation between the actual sand discharge volume and the theoretical value was $\leq 5\%$, meeting the design requirements. Typical test data are shown in Table 3.

Table 3. Three Scheme comparing

No.	Sand Concentration(%)	Theoretical Sand Volume(kg/min)	Actual Sand Volume(kg/min)	Deviation Value(%)
1	5	16.8	17.2	2.38
2	10	33.7	32.8	2.67
3	15	50.5	49.2	2.57

- 2) Flow and pressure test: The system's flow and pressure under various working conditions were tested. The results showed that the system's discharge flow could reach $118 \text{ m}^3/\text{h}$, and the maximum discharge pressure was 0.55 MPa, far exceeding the design specifications.
- 3) 8-hour full-load temperature rise test: The equipment operated at full load for 8 hours, and the temperature changes of the hydraulic system were monitored. At the end of the test, the maximum temperature of the hydraulic oil was 58°C (environmental temperature was 25°C), with a temperature rise of $33^\circ\text{C} \leq 50^\circ\text{C}$, indicating stable system operation.
- 4) Explosion-proof performance test: A third-party testing institution was commissioned to conduct the explosion-proof performance test. The equipment met the Exdib [Mb] explosion-proof grade requirements and obtained the safety certificate for mining products (MA mark).

5. Conclusion

A 1m^3 electric-driven liquid sand mixing unit in a coal mine underground adopts an electric-driven liquid drive method and a load-sensitive hydraulic system, achieving efficient, energy-

saving and safe operation, and meeting the requirements of hydraulic fracturing operations in the coal mine underground. The test verification shows that all performance indicators of the equipment have reached or exceeded the design requirements, and the explosion-proof performance complies with the underground safety regulations.

The main innovations of this equipment are:

- 1) Adopting an electric-driven liquid drive architecture, reducing the exposure of electrical components and improving explosion-proof safety;
- 2) Applying a load-sensitive hydraulic system to achieve on-demand oil supply, reducing energy consumption by more than 15%;
- 3) Overall skid-mounted design, compact structure, and suitable for operations in narrow underground spaces.

In the future, the automation control level of the equipment can be further optimized, remote monitoring functions can be developed, and the intelligence level of the equipment can be improved, providing better equipment support for hydraulic fracturing operations in the coal mine underground.

References

- [1] Yang yunfan, Liu zhiqiang, Gao xianbo,etl. Research Progress on Hydraulic Fracturing Technology in Underground Coal Mines[J]. Journal of China Coal Society, 2020,45(5):1800-1810.
- [2] JOHNSON A F, HOLZAPFEL M. Application of load-sensitive hydraulic systems in mining equipment[J]. Mining Engineering, 2019, 71(3): 45-50.
- [3] Jia dongqin, Ke ping. Design Specifications and Applications of Mine Explosion-proof Electrical Equipment[C]. Proceedings of the Academic Annual Conference of the China Coal Society, 2021: 120-125.
- [4] State Administration of Work Safety. Coal Mine Safety Regulations [S]. Beijing: China Coal Industry Publishing House,2022.
- [5] Wei, L. Design of control system for mining hydraulic equipment based on PLC [D]. Master's thesis, Dalian University of Technology],2020.
- [6] Zhao, Y. D. Hydraulic transmission and control. China Machine Press. (Original work published in Chinese, 2018: 150–165.
- [7] National Standard of the People's Republic of China. Explosive atmospheres-Part 1: General requirements for equipment (GB/T 3836.1-2021).
- [8] Li, D. M., Zhu, S. M., Zhao, Y. Z., et al. Research on electro-hydraulic control system for automatic anti-jamming drilling in coal mines [J]. Journal of Chongqing University, 2022,45(2), 114–124.
- [9] Zhang, X. P., Xie, P., & Fu, J. G. Design and research of a modular IoT electric-driven sand mixing skid. Plant Maintenance Engineering, 2022(21), 24–26.
- [10] Jia, B. Y., Chen, D. D., Sun, S. Q., et al. A closed high-pressure hydraulic cyclone continuous sand mixing and supply device and system for underground coal mines, Patent No. CN215654747U, 2022.
- [11] Sun, Y. F., Liu, Z. Q., Wang, Z. B., et al. Performance test and simulation analysis of mining high-pressure large-flow electro-hydraulic proportional valves. Hydraulics & Pneumatics, 2023,47(2), 89–96.
- [12] Wang, G. F., Du, Y. B., Meng, X. J., et al. Research and prospect of electro-hydraulic control system for intelligent hydraulic supports in coal mines. Coal Science and Technology, 2021,48(7), 1–9.
- [13] Li, Y. Research on cooperative control method for electro-hydraulic control system of hydraulic support groups based on industrial Internet [D], Master's thesis, Taiyuan University of Technology, 2021.