Frontiers in Engineering
ISSN Print: 3104-4298
ISSN Online: 3104-4301
CD ISSN: 3104-431X
https://doi.org/10.63313/FE.9007

Research on Automatic Pressure-Holding and Flow-Limiting Device for Sealing Bladder Based on Embedded Platform

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How to cite this paper: Chen, J. (2026). Research on automatic pressure-holding and flow-limiting device for sealing bladder based on embedded platform. *Frontiers in Engineering*, *1*(2), 44–54. ISSN Print: 3104-4298; ISSN Online: 3104-4301.
https://doi.org/10.63313/FE.9007
Published: 2026-05-13

Abstract

Gas drainage is a key measure to guarantee underground operation and miners' safety, while grouting hole sealing, as the principal technical method for gas drainage, still exists many technical problems. This paper develops an automatic pressure-holding and flow-limiting system based on an embedded platform, consisting of hardware and software designs. The hardware comprises a core control module based on STC12C5A60S2, an LCD1602 display module, a relay module, a pressure sensor, a flow sensor, a two-position three-way solenoid valve, and a check valve. For software design, C-language programming in the Keil uVision5 environment is adopted to realize communication with pressure and flow sensors and control of the relay module. Taking the "two-seal one-injection" pressurized bladder sealing process as an example, in the grouting and expansion stage of the sealing bladder, when the detected pressure and flow values are lower than the set thresholds, the STC12C5A60S2 chip outputs a low-level signal to the relay module, keeping the relay inactive; the circuit of the two-position three-way solenoid valve is disconnected, and the outlet of the solenoid valve is connected to the sealing bladder for normal grouting. When the detected pressure or flow value exceeds the set thresholds, the STC12C5A60S2 chip outputs a high-level signal to activate the relay module, connecting the solenoid valve circuit and linking the solenoid valve outlet to the atmosphere, thus shutting down the grouting pump. Similarly, in the stage of sealing fractures in the middle section of the bladder with non-coagulating flexible gel, grouting continues when the pressure is below the set threshold and stops when the pressure exceeds the threshold. The system automatically regulates grouting pressure within a certain range, enabling "secondary sealing" and "tertiary sealing". This system improves the reliability of grouting hole sealing by means of pressure maintaining and flow limiting, thereby effectively increasing the gas drainage concentration.

Keywords

Single Chip Microcomputer; Grout sealing; Embedded platform; Pressure-Holding and flow-limiting; Cooperative control

1. Introduction

Coal plays a vital role in global energy supply and industrial development, safeguarding China's energy security and high-quality economic development [1-2]. The livelihood of people, power production, and economic growth in many countries rely on coal. Gas is one of the major hazards in coal mining, severely threatening the safety of coal mine production [3-4]. Gas control is crucial before coal mining, and gas drainage technology improves the safety of mine mining [5]. Rational gas drainage from coal seams not only reduces environmental pollution but also enables the reuse of extracted gas. As the main method of gas drainage, grout sealing faces problems such as borehole air leakage due to incomplete sealing and sealing damage caused by roadway excavation. Once a borehole leaks gas, coal seam gas migrates into fractures in the borehole or the roadway, resulting in low gas drainage concentration and a high risk of gas explosions, which seriously endangers the lives of underground workers. Therefore, sealing technology is particularly important [6-7]. At present, there are four main sealing methods for gas drainage boreholes in Chinese coal mines: cement mortar sealing, polyurethane sealing, "two-seal one-injection" sealing [8-9], and secondary sealing. Most sealing devices adopt bladder-type sealers, mainly relying on fixed-value burst valves, pressure-limiting control valves, and other components to achieve pressure-limited sealing. However, traditional grout sealing is characterized by uncontrollable pressure, unstable flow rate, and delayed manual intervention, leading to over-expansion damage or insufficient sealing of sealers and poor fracture sealing, making it unsuitable for scenarios requiring high-precision pressure control. This paper adopts an automatic pressure-holding and flow-limiting device for grout sealing based on an embedded platform, abandoning traditional mechanical devices and using single-chip microcomputers and sensors. It boasts advantages such as strong real-time performance, high precision, and adjustability [10-11], ensuring stable sealing pressure and protecting sealers from high-pressure damage during grouting expansion, thus playing a key role in grout sealing.

2. System Composition and Overall Scheme

The automatic pressure-holding and flow-limiting device for grout sealing consists of a core control module based on STC12C5A60S2 [12], an LCD1602 display module, a relay module [13], a pressure sensor, a flow sensor, a two-position three-way solenoid valve [14], and a check valve. The overall scheme structure of the pressure-holding and flow-limiting system is shown in Figure 1.

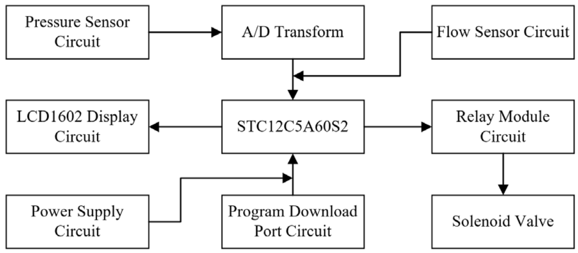

Figure 1. Overall Structure of the Pressure-Holding and Flow-Limiting System

The system operation process: the core control module based on STC12C5A60S2 processes the voltage signal from the pressure sensor and the pulse signal from the flow sensor, converts them into corresponding pressure and flow values, compares them with set thresholds, and outputs high/low-level signals to control the working state of the relay, realizing power-on and power-off of the solenoid valve. By switching the outlet of the two-position three-way solenoid valve, the system controls whether grouting is supplied to the sealing device.

3. System Hardware And Software Design

3.1. Pressure Sensor Circuit Design

The pressure sensor adopts the JVMO-131 pressure transmitter with a measuring range of 0–2.5 MPa. The JVMO-131 sensing element detects pressure and generates a corresponding analog electrical signal, which is amplified and processed by the internal circuit and converted into a standard 0–5 V voltage signal for output via the signal line, received by the P10 pin of the chip. After A/D conversion, the corresponding voltage value is read, and the actual pressure detected by the sensor is obtained using the one-to-one correspondence between the measuring range and voltage (1 V voltage increase corresponds to 500 KPa pressure rise; e.g., 2 V voltage equals 1000 KPa pressure) and displayed on the LCD1602 screen. The schematic diagram of the pressure transmitter is shown in Figure 2. The calculation formula is as follows:

$$P = 500Getchar\,. \tag{1}$$

P: pressure value, KPa; Getchar: voltage value, V.

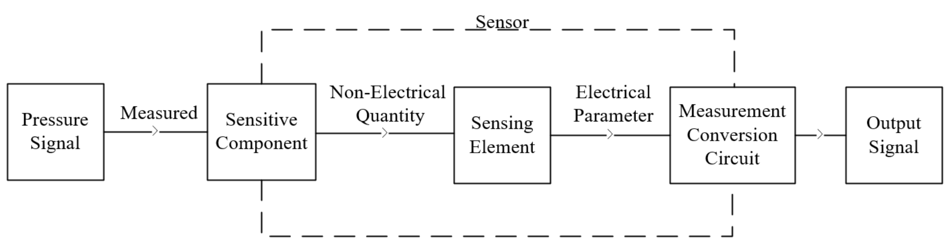

Figure 2. Schematic Diagram of the Pressure Transmitter

The ADC module on the STC12C5A60S2 microcontroller can only convert voltage signals. To convert current signals, resistors or current-voltage modules are required to convert current into corresponding voltage for ADC reception, introducing unavoidable systematic errors. Given the short signal transmission distance, a voltage-output pressure sensor is selected.

3.2. Flow Sensor Circuit Design

The flow sensor adopts the YF-S201 flow sensor, composed of a shell valve body, a magnetic rotating component, and a Hall sensor. After power-on and program initialization, liquid flows through the valve body and the magnetic rotating component, driving the propeller-type rotor to rotate the magnet. The rotating magnet forms a current with the Hall sensor, and the Hall sensor outputs one electrical pulse per revolution. 450 pulses correspond to a water flow of 1 L, i.e., 1 pulse equals 0.002222 L. The cumulative flow calculation formula is as follows:

$$F = 0.002222 Pulse \quad (2)$$

F: flow rate, L; Pulse: number of pulses.

The STC12C5A60S2 microcontroller pin detects pulse signals to calculate cumulative water flow data, which is displayed on the LCD1602 screen.

3.3. Display Circuit Design

The LCD1602 is a common and simple display device capable of showing 2×16 digits or characters, meeting system requirements. The minimum system board of the microcontroller is equipped with integrated pin interfaces, requiring only corresponding insertion of the display screen. The LCD1602 writes data and generally does not use the data reading function. When setting the LCD1602 operating mode, RS and RW are set to low level, and EN is set to high level to write data; when displaying data on the screen, RS is set to high level with RW and EN unchanged to complete data display. The circuit schematic of LCD1602 is shown in Figure 3.

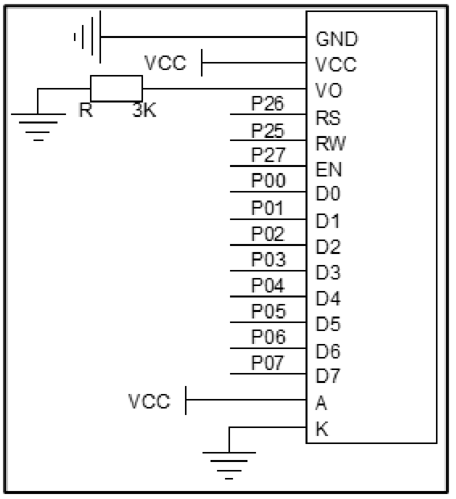

Figure 3. Circuit Schematic of LCD1602

To use the LCD1602, initialize it first, select the display position on the screen, write the data to be displayed into the LCD1602 RAM, and complete display after processing. The schematic diagram is shown in Figure 4.

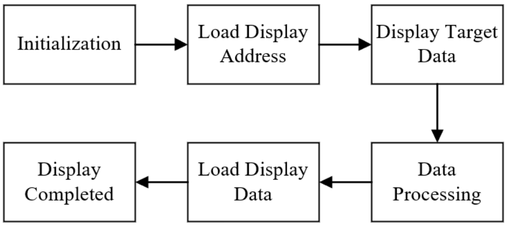

Figure 4. Schematic Diagram of LCD1602 Display Principle

3.4. Control Circuit Design

The solenoid valve operates at 24 V, while the microcontroller's high level is 5 V with no driving capability. Therefore, an external 24 V power supply and a relay module are required to control the solenoid valve. The system control function is realized by the relay module and the two-position three-way solenoid valve.

The relay module is an optocoupler-isolated electrical device acting as a switch in the circuit, supporting high/low-level triggering. The circuit switch is controlled by a high/low-level signal from one microcontroller pin. Input terminals: VCC, GND, IO port; output terminals: NC (normally closed), COM (common), NO (normally open). The NO terminal is normally open, and the NC terminal is normally closed. The normally open contact is disconnected when the relay coil is de-energized and closes when the coil is energized due to electromagnetic force, connecting the disconnected circuit.

The relay module is set to high-level triggering according to system characteristics. When the system pressure or flow is below the set threshold, the IO port outputs no signal, the circuit is disconnected, the solenoid valve is de-energized, and NC is coupled with COM; when the pressure or flow exceeds the threshold, the IO port outputs a high-level signal, NO is coupled with COM, the circuit is connected, and the solenoid valve is energized. The optocoupler-isolated relay consists of a photocoupler and a relay, widely used in industrial and electronic fields for electrical isolation and signal transmission, featuring simple principle, low cost, and high system safety and stability. The control circuit schematic is shown in Figure 5.

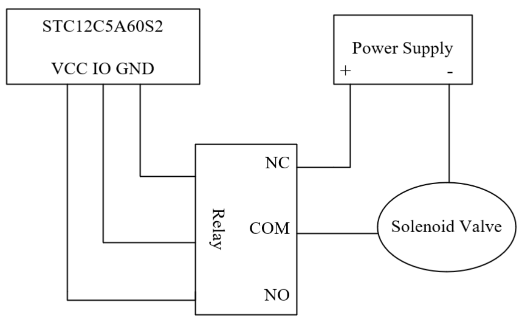

Figure 5. Schematic Diagram of the Control Circuit

The two-position three-way solenoid valve is common in industrial control (two positions: on/off; three ports: inlet P, outlet A, outlet B), composed of an electromagnetic coil, valve body, and spring. When energized, the electromagnetic coil is activated, generating a magnetic field to push the spool and change its position; liquid flows through outlet B, blocking outlet A. When de-energized, liquid flows through outlet A, blocking outlet B.

The solenoid valve switches fluid channels via power on/off, quickly and reliably changing flow direction to realize flexible system control. The working state schematic of the two-position three-way solenoid valve is shown in Figure 6.

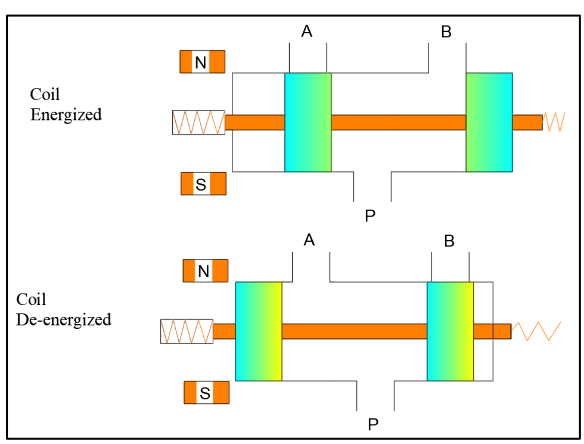

Figure 6. Working State Schematic of the Solenoid Valve

3.5. System Software Design

The single-chip programming software for the pressure-holding and flow-limiting system is Keil uVision5, and the programming language is C language. C language is efficient, structured, and readable, suitable for embedded system software development [15]. The USB-to-serial driver is CH340, acting as a bridge for interaction, debugging, and program downloading between the USB interface and the microcontroller. The program burning software is STC-ISP.

The overall software design flow: modular programming in C language on Keil uVision5, including the main function, LCD1602 modular code, ADC modular code, and USART modular code. After program writing and debugging, the program is downloaded to the STC12C5A60S2 chip via the CH340 driver on STC-ISP, completing the system software design. The program flow chart is shown in Figure 7.

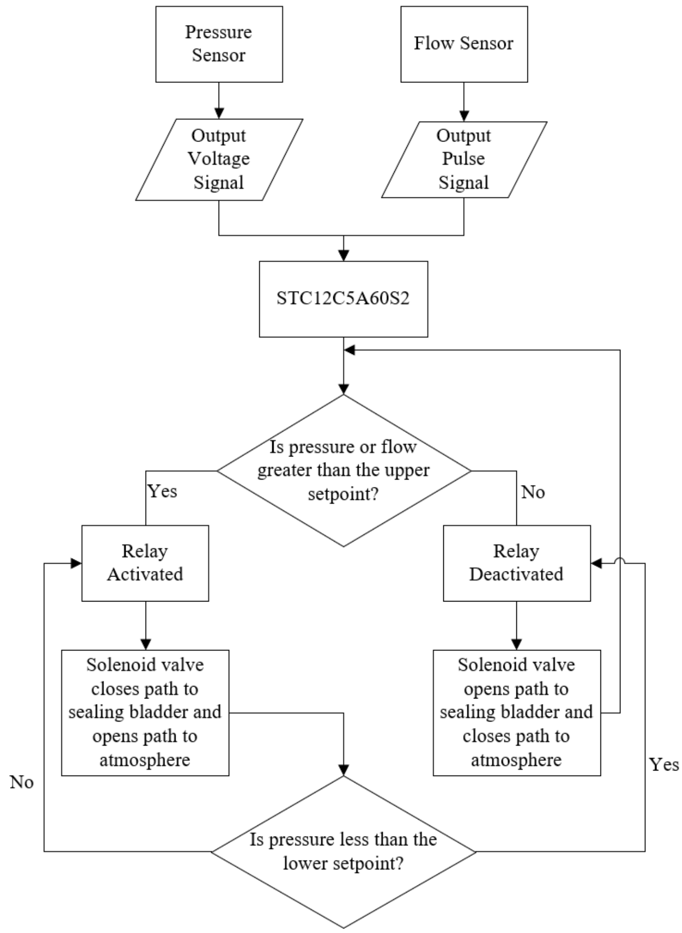

Figure 7. Program Flow Chart

The pressure sensor outputs a voltage signal converted to a corresponding pressure value via the ADC module. The flow sensor outputs a pulse signal directly recognized by the microcontroller. When the grouting pipe is connected to the sealing bladder, if the detected pressure and flow values are lower than the set thresholds, the STC12C5A60S2 chip outputs a low-level signal to deactivate the relay module; the two-position three-way solenoid valve circuit is disconnected, and outlet A of the solenoid valve is connected to the sealing bladder for normal grouting. When the detected pressure or flow value exceeds the thresholds, the chip outputs a high-level signal to activate the relay, connecting the solenoid valve circuit and linking outlet B to the atmosphere, shutting down the grouting pump and stopping grouting. When sealing the middle section of the bladder and fractures with flexible gel, grouting pressure decreases; grouting continues when pressure is below the lower threshold and stops when exceeding the upper threshold, maintaining dynamic pressure balance for pressure-holding and effectively improving sealing effect and gas drainage concentration.

4. Laboratory Experiments

The device is connected between the sealing bladder and the grouting pump. The laboratory test setup of the pressure-holding and flow-limiting system is shown in Figure 8.

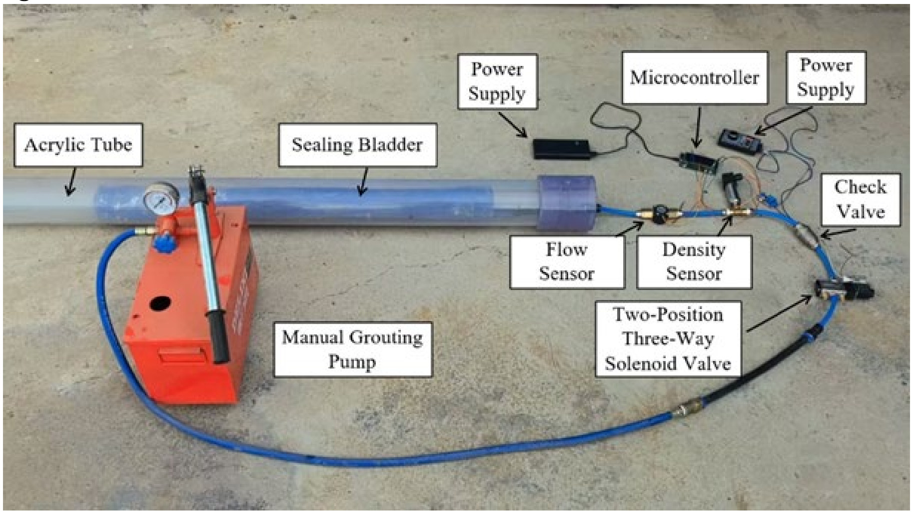

Figure 8. Laboratory Test Setup of the Pressure-Holding and Flow-Limiting System

4.1. Sensor Calibration

For the YF-S201 flow sensor, 1 L of clean water is prepared. The sensor is reset before water flow, with the LCD1602 showing 0 flow. After passing 1 L of water through the sensor, the cumulative flow displayed is 1.007 L, with an error of less than 1%, indicating high accuracy and no need for calibration.

For the JVMO-131 pressure transmitter, after circuit connection, the voltage read via the serial port assistant is 0.4 V, and the pressure displayed on the LCD1602 is 200

KPa. This error is systematic, caused by the weak voltage of the STC12C5A60S2 minimum system board detected by the pin. The systematic error is eliminated by subtracting 0.4 V from the detected voltage in the code. The pressure transmitter is connected to the pipeline, and the pressure readings from the transmitter and the grouting pump pressure gauge are compared, with an error of less than 1%, requiring no code modification for calibration.

4.2. Determination of Maximum Pressure and Flow Bearing Capacity

The test sealing bladder is a two-seal one-injection bladder-type sealer. One side of the two-position three-way solenoid valve is connected to the grouting pump, and the flow sensor side is connected to the sealing bladder; the bladder is inserted into an acrylic tube, and the manual grouting pump is operated for grouting. When the bladder ruptures, the pressure and flow displayed on the module are recorded as the ultimate pressure and flow bearing capacity. Test data are shown in Table 1.

Table 1. Ultimate Pressure and Flow Bearing Capacity of a Single Bladder

Numble	Ultimate Pressure (MPa)	Ultimate Flow (L)
1	0.62	3.57
2	0.58	3.48
3	0.62	3.55
4	0.68	3.64
5	0.66	3.60
6	0.68	3.55
7	0.65	3.50
8	0.65	3.58
9	0.64	3.67
10	0.60	3.61

The ultimate pressure bearing capacity is defined as the minimum pressure value P_{min} in the test data, and the ultimate flow bearing capacity as the minimum flow value L_{min}. The upper pressure limit $P_{upper}<P_{min}$, upper flow limit $L_{upper}<L_{min}$, and lower pressure limit P_{lower} (set for sealing the middle bladder section and fractures) satisfies $P_{lower}<P_{upper}$. Here, P_{min}=0.58MPa, L_{min}=3.48L. The upper pressure and flow limits are set slightly lower than the minimum test values to reserve a tolerance range, preventing bladder rupture due to over-expansion while ensuring full contact between the bladder and the borehole wall. P_{upper}, L_{upper}, and P_{lower} can be adjusted on-site for optimal sealing. The measured P_{upper}, L_{upper}, and P_{lower} are written into the core control module program. The "two-seal one-injection" bladder-type sealer has two bladders; their ultimate pressure bearing capacity is the same as that of a single bladder, and the ultimate flow capacity is approximately twice that of a single bladder.

5. Conclusions

(1) The embedded system features excellent real-time performance, enabling control and monitoring of multiple processors and devices to realize complex software-hardware interaction. The embedded-platform-based automatic pressure-holding and flow-limiting device for sealing bladders detects pressure and flow in real time, realizes pressure-flow cooperative control grouting, and responds rapidly, improving sealing effect.

(2) The device effectively solves problems in traditional grout sealing, including uncontrollable grouting pressure and flow, delayed manual intervention leading to bladder over-expansion damage or sealing failure, and poor fracture sealing. It significantly improves construction efficiency and gas drainage concentration, with promising application prospects.

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