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INFRARED SPECTROSCOPY-BASED ONLINE MONITORING SYSTEM FOR MICROBUBBLE CONCENTRATION

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Abstract: To address the urgent need for the real-time and precise monitoring of microbubble concentrations in industrial fluids, an online monitoring system for microbubbles was developed based on the principles of infrared spectroscopy sensing and light intensity attenuation, featuring an architecture that integrates array-based infrared photoelectric sensing with cloud collaboration. A 'three-emitter, three-receiver' array-based infrared detection scheme is adopted to effectively mitigate the issue of poor sample representativeness associated with single-optical-path detection in complex fluid phases. Centered around a Raspberry Pi as the primary controller, the system incorporates precise photoelectric signal conditioning circuitry, high-resolution analog-to-digital conversion modules, and industrial communication links. A dual-channel data communication architecture based on the RS485 bus and the MQTT IoT protocol was established. Testing demonstrates that the system exhibits high real-time performance, strong anti-interference capability, and excellent digital management features, enabling both on-site real-time monitoring of microbubble concentrations and remote visualization via a cloud dashboard.
Keywords: Microbubble concentration; Infrared spectroscopy; Cloud monitoring; Online monitoring

1 INTRODUCTION

Owing to their unique physical properties—such as minute size, large specific surface area, slow rising velocity in liquids, and self-pressurized dissolution—microbubbles have demonstrated extensive application value across various industrial fields [1]. In environmental engineering, microbubbles are commonly utilized for highly efficient wastewater treatment and water body remediation; in biomedicine, they play a crucial role as ultrasound contrast agents and drug delivery vehicles [2]; meanwhile, in industries such as mineral flotation, precision cleaning, and food processing, microbubble technology has emerged as a key approach to enhancing process efficiency [3]. In the petroleum industry, microbubble flooding serves as a cutting-edge technology for enhanced oil recovery (EOR). Its effectiveness in mobility control and gas channeling suppression is highly dependent on the concentration distribution and stability of the microbubble system [4]. Consequently, achieving real-time and precise monitoring of microbubble concentration has become a core requirement for evaluating displacement efficiency. Currently, existing monitoring techniques predominantly rely on conductivity methods, acoustic attenuation methods, and traditional contact-based optical transmission methods [5]. However, in complex high-pressure pipeline environments, these methods often suffer from limitations such as poor real-time performance, susceptibility to fluid salinity interference, and sensor fouling, making it difficult to meet the precision requirements for the online sensing of microbubble concentration in industrial field applications.

Focusing on the characteristics of bubbles in water, researchers have conducted various exploratory detection studies based on electrical conductivity, acoustic waves, and optical scattering. For instance, Sun Kexia et al. [6] proposed using a double-sensor conductivity probe technology to measure local bubble parameters, designing a conductivity probe system capable of rapidly and reliably calculating these parameters. Zhao et al. [7] utilized a digital high-speed camera system and a dual-sensor conductivity probe to experimentally investigate the interfacial area concentration, void fraction, and average bubble diameter of an air-water bubble flow within a vertical transparent tube with a 40 mm inner diameter. Ultrasonic detection methods [8] can also be applied to bubble detection; however, they may cause damage to the internal bubble structure of the measured target. Zhan et al. [9] theoretically proposed a novel bubble detection technology in rotating solutions based on light intensity and Mie scattering theory, enabling the calculation of light intensity distribution in all directions. In the field of underwater pipeline bubble detection, several established methods currently utilize acoustic waves to detect bubbles released from pipelines [10]. One such method involves using acoustic sensors mounted on the pipeline surface to detect the acoustic waves generated by bubbles leaking from orifices [11]. Nevertheless, due to the weak acoustic signal strength and complex background noise, the detection performance remains unsatisfactory.

In summary, addressing the limitations of conventional single-beam detection and visual recognition in complex pipeline environments, this study develops an infrared photoelectric monitoring system. By employing a multi-path infrared sensing method with a 'three-emitter, three-receiver' configuration, this approach more comprehensively captures the signal attenuation characteristics caused by microbubbles within the pipeline, effectively enhancing the representativeness and stability of the monitoring data under complex flow conditions. Supported by high-precision photoelectric signal conditioning circuitry at the hardware level, the system realizes standardized wired communication via RS485 (Modbus-RTU protocol) and wireless communication through an MQTT IoT platform.

2 PRINCIPLES AND METHODS OF MULTI-PATH INFRARED SENSING FOR MICROBUBBLE CONCENTRATION

2.1 Sensing Principle

The monitoring of microbubble concentration is primarily based on the principle of infrared spectral attenuation. When infrared light of a specific wavelength passes through a gas-liquid mixture containing microbubbles, the light waves are subjected to absorption, reflection, and scattering by the microbubbles, resulting in the attenuation of radiation intensity at the receiving end. Under actual operating conditions, the distribution of microbubbles within the pipeline is inherently random and heterogeneous, rendering traditional single-beam detection susceptible to significant instantaneous deviations. Consequently, this study employs a multi-path parallel detection scheme. By acquiring transmission signals from various spatial positions and utilizing weighted average and data fusion algorithms, this approach can more objectively reflect the overall concentration characteristics of the fluid within the pipeline.

2.2 Detection Method

The detection method of the monitoring system is illustrated in Figure 1. Based on the principle of photoelectric transmission attenuation, a stable light beam is emitted by the emitter array at the top of the device, penetrating the optical window into the pipeline. As the light traverses the gas-liquid mixture containing microbubbles, its energy attenuates due to the absorption and scattering effects of the microbubbles. The corresponding receiver array at the bottom captures the transmitted optical signals and converts them into electrical signals. By analyzing the correlation between the degree of light intensity attenuation and the microbubble concentration, in conjunction with the multi-path spatial layout, real-time and stable monitoring of the microbubble concentration within the pipeline is achieved.

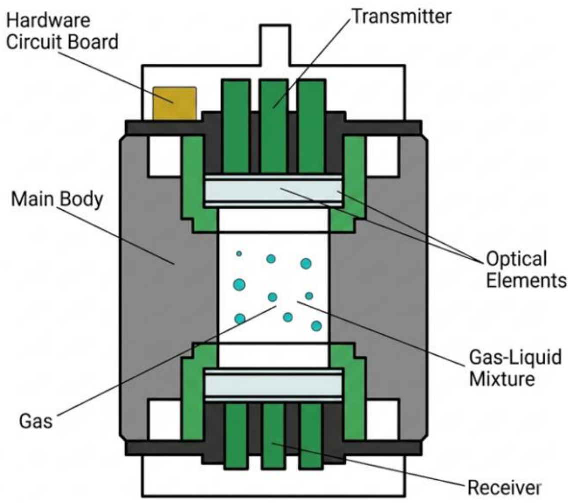

Figure 1 Schematic Diagram of the Detection Method

The system's hardware circuitry is integrated within the device enclosure. A signal processing board amplifies, filters, and performs analog-to-digital (A/D) conversion on the weak current signals captured by the three receivers. Equipped with an industrial-grade communication module, the system supports RS485 bus communication utilizing the standard Modbus-RTU protocol, which facilitates seamless integration with Programmable Logic Controllers PLC or host computer systems. Furthermore, an IoT gateway function is integrated to enable the uploading of real-time monitoring data to a cloud server, thereby realizing remote monitoring via mobile terminals and historical data traceability.

3 ARCHITECTURE OF THE MICROBUBBLE CONCENTRATION ONLINE MONITORING SYSTEM

The overall architecture of the microbubble concentration online monitoring system adopts a three-layer hierarchical structure comprising the device perception layer, the edge control layer, and the cloud application layer. The edge control layer enables real-time data acquisition and preprocessing, while local data transmission and cloud-based remote monitoring are implemented through industrial standard protocols, as illustrated in Figure 2.

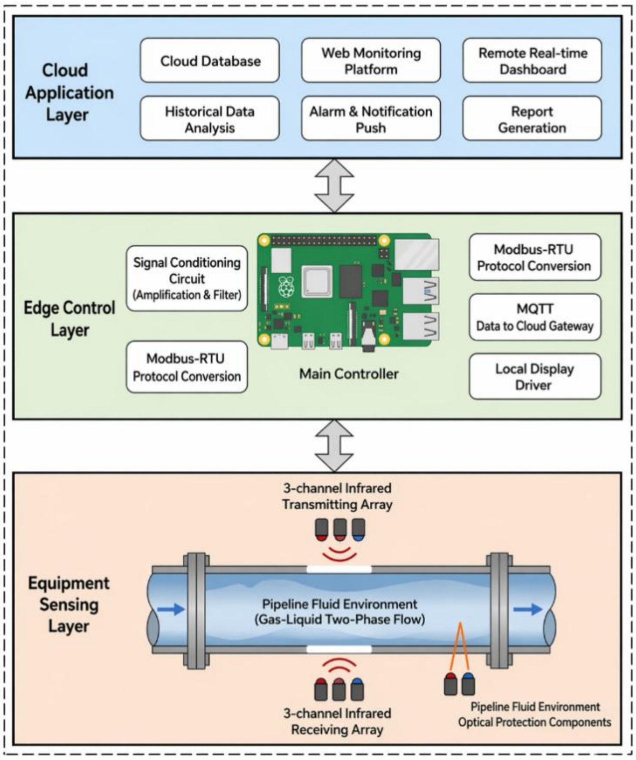

Figure 2 Monitoring System Architecture

The device perception layer is directly deployed at the industrial pipeline site as the source of detection data. It utilizes three sets of parallel infrared emission and reception units to form an arrayed detection optical path. Compared with a single-optical-path structure, the triple-terminal array effectively reduces random measurement errors caused by the non-uniform distribution of microbubbles in gas-liquid two-phase flows, significantly enhancing the spatial representativeness of the sampled data. To protect the precision photoelectric components, high-transmittance sealing windows are integrated to prevent erosion or contamination of the sensors by high-pressure fluids within the pipeline.

The edge control layer utilizes a Raspberry Pi as the core control unit, undertaking the tasks of conversion and distribution from analog signals to digital information. Precision amplification and low-pass filtering are performed on the weak raw signals output by the receiver array to eliminate electromagnetic noise from industrial sites, ensuring that the data entering the control unit possess a high signal-to-noise ratio (SNR). The system converts the monitoring data into industrial-standard RS485 signals to facilitate compatible integration with on-site PLC or host computer systems. Simultaneously, by leveraging the MQTT lightweight transmission protocol, the processed data are pushed to the cloud platform in real-time.

The cloud application layer aggregates decentralized monitoring points into digitalized information, providing comprehensive management capabilities. Users can retrieve real-time on-site operational parameters at any time through the Web monitoring backend.

4 DESIGN OF THE MICROBUBBLE MONITORING CONTROL SYSTEM

The control system serves as the core of the monitoring apparatus, responsible for photoelectric signal processing and data transmission. Utilizing an edge computing unit as the central hub, the system integrates precision conditioning circuitry to achieve synchronous sampling of the three-emitter, three-receiver infrared array. Through dual-channel output via the RS485 wired bus and the cloud platform, the system effectively suppresses industrial field interference, ensuring the real-time capability and consistency of the monitoring data. Furthermore, the system supports instantaneous on-site display and achieves remote digital management, providing a stable hardware platform and data assurance for the evaluation of microbubble-enhanced oil recovery.

4.1 Signal Function Module

As illustrated in Figure 3, the system utilizes a Raspberry Pi as the control core to construct a complete circuit architecture extending from a DC 24V power supply to multi-channel outputs. Power stability and light source driving are ensured through voltage stabilization and relay modules, while signal enhancement and digital sampling are implemented utilizing operational amplifier modules and analog-to-digital (AD) conversion modules. Finally, the monitoring data are transmitted via a dual-path mechanism through the Modbus-RTU protocol and wireless networks, forming an industrialized integrated monitoring solution that integrates photoelectric sensing, precision signal processing, and cloud collaboration.

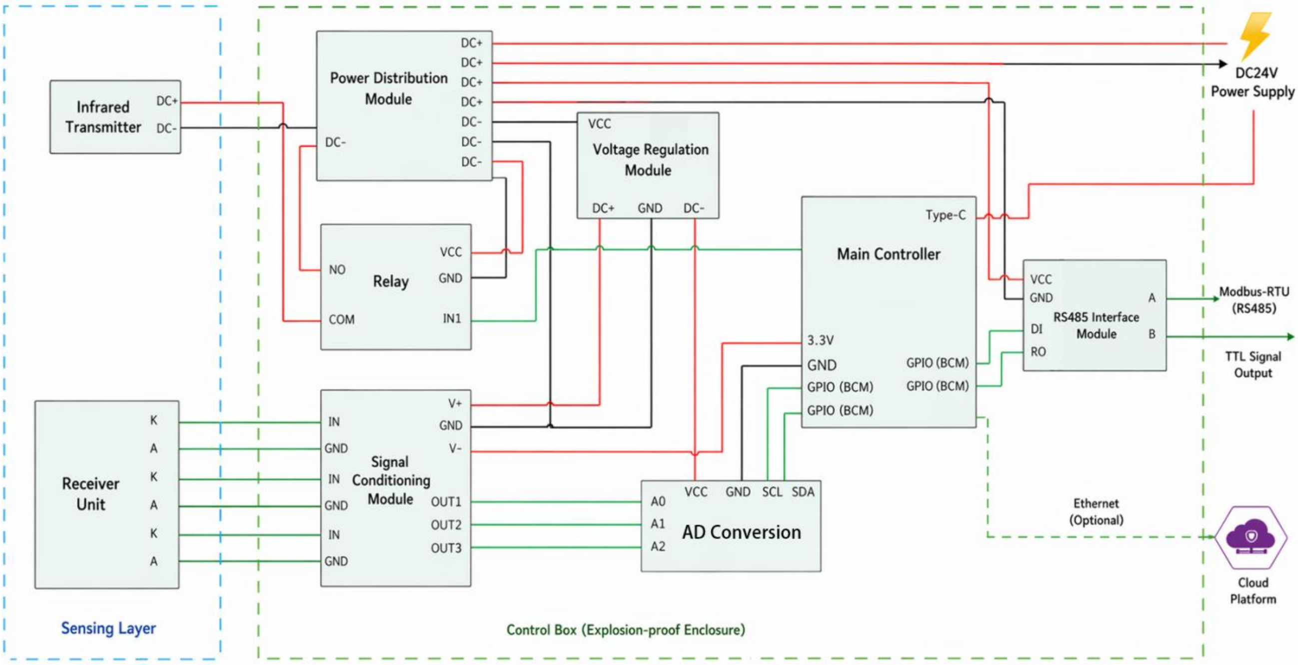

Figure 3 Signal Function Module Diagram

4.2 Control Flow

As illustrated in Figure 4, the port self-check and communication protocol connection are first completed, followed by entry into the main loop for synchronous acquisition of raw ADC values from the three-channel infrared sensors. Median filtering and weighted algorithms are applied to enhance data precision. After intercepting invalid signals via an anomaly determination mechanism, the system transmits the processed concentration data in parallel to the local terminal and cloud platform through the RS485 bus and MQTT protocol, ensuring the efficiency and reliability of the entire monitoring process.

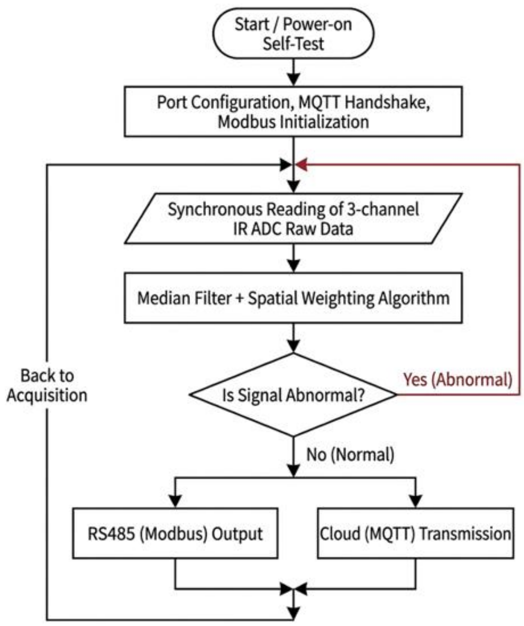

Figure 4 Control Logic Flowchart

4.3 Display Page

The cloud monitoring interface of the system achieves a digitized and intuitive visualization of microbubble concentration and operational parameters. Real-time data cards at the top of the interface synchronously present ambient temperature and pressure, core microbubble concentration, and sampled values from the three-channel sensor array. Furthermore, the integrated dynamic trend curves at the bottom enable long-term tracking and visual analysis of concentration fluctuations and environmental variations (Table 5).

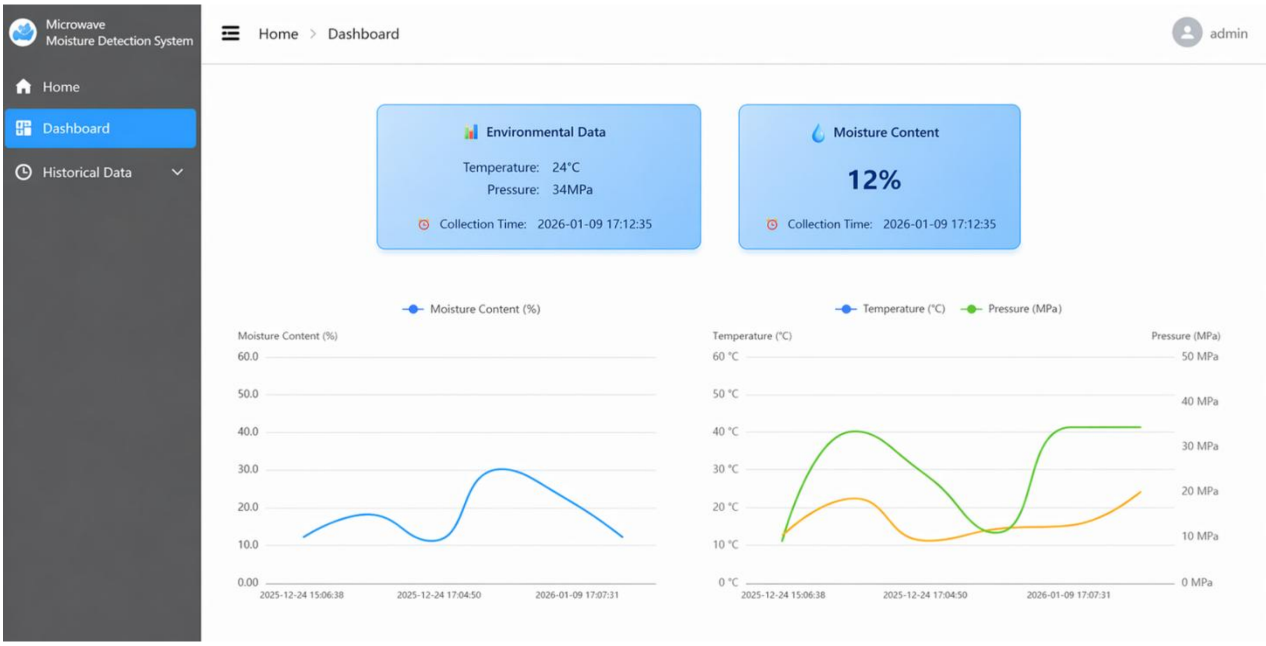

Figure 5 Cloud Page

5 CONCLUSION

This paper develops an online monitoring system for microbubble concentration that integrates perception, communication, and cloud-based visualization. The reliability of signal capture is enhanced through an arrayed infrared transceiver structure, and local data processing with dual-channel output (RS485 and cloud) is achieved by leveraging an edge computing unit. Experimental results demonstrate that the system addresses the challenge of real-time microbubble concentration monitoring under complex operating conditions, while simultaneously enhancing digital management through its cloud transmission mechanism. This research achieves real-time, precise perception of microbubble concentration and system stability, providing robust data support for the in-depth investigation of the evolutionary laws and physical characteristics of microbubbles.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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