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Online Monitoring Of Geological Co_2 Storage And Leakage Based On Wireless Sensor Networks

A. Anusha[1], Dr. B. Jeyaraman[2]

[1, 2] *(PG Scholar, Professor, Department of EEE, Sriram Engineering College Department of EEE, Sriram Engineering College, Perumalpattu, Thiruvallurdist, Tamil Nadu.)*

Abstract: *A remote online carbon dioxide (CO_2) concentration monitoring system is developed, based on the technologies of wireless sensor networks, in allusion to the gas leakage monitoring requirement for CO_2 capture and storage. The remote online CO_2 monitoring system consists of monitoring equipment, a data center server, and the clients. The monitoring equipment is composed of a central processing unit (CPU), air environment sensors array, global positioning system (GPS) receiver module, secure digital memory card (SD) storage module, liquid crystal display (LCD) module, and general packet radio service (GPRS) wireless transmission module. The sensors array of CO_2, temper-ature, humidity, and light intensity are used to collect data and the GPS receiver module is adopted to collect location and time information. The CPU automatically stores the collected data in the SD card data storage module and displays them on the LCD display module in real-time. Afterwards, the GPRS module continuously wirelessly transmits the collected information to the data center server. The online monitoring WebGIS clients are developed using a PHP programming language, which runs on the Apache web server. MySQL is utilized as the database because of its speed and reliability and the stunning cross-browser web maps are created, optimized, and deployed with the Open Layers JavaScript web-mapping library. Finally, an experiment executed in Xuzhou city, Jiangsu province, China is introduced to demonstrate the implementation and application.*

Index Terms: *CO_2 capture and storage (CSS), general packet radio service (GPRS), global positioning system (GPS), remote online leakage monitoring, wireless sensor networks (WSN).*

I. Introduction

Atmospheric concentrations of the key greenhouse gas (GHG) carbon dioxide (CO_2) well above pre-industrial levels constitute the main cause for the predicted rise at average surface temperature on Earth and the corresponding change of the global climate system.CO_2 Capture and storage (CCS) is on the one hand an effective way to realize effective greenhouse gas storage, and on the other to improve oil and gas production [2]. Many countries such as the United States, Japan, and Canada are in search of effective approaches for CO_2 storage in either geological formations or ocean. In China, the first demonstrative industrial project of CO_2 storage has come into operation in Shenhua mine area. However, once CO_2 leaks from the storage reservoir, all the efforts human beings have made to fight global warming would be go down the drain. Therefore, what is in needed after the geological CO_2 storage is long-term terrain monitoring of the greenhouse gas leakage, which is absolutely crucial to help ensure that geologic sequestration of CO_2 is safe. For this reason, the development of remote online monitoring system is of great significance to geological CO_2 storage and leakage warning.

Recent advances in information and communication tech-nologies have resulted in the development of more efficient, low cost and multi-functional sensors. These micro-sensors can be deployed in wireless sensor networks (WSN) to monitor and collect air environmental information such as CO_2 concentration, temperature, humidity, light intensity, air pressure, wind power, wind direction, etc. The information is then wirelessly transmitted to data center server where they are integrated and analyzed for evaluating of geological CO_2 storage and leakage. Deploying sensor networks allows inaccessible areas to be covered by minimizing the sensing costs compared with the use of separate sensors to completely cover the same area [3]. The remainder of this paper is as follows. Section 2 presents the backgrounds of CCS leakage monitoring based on WSN and their related issues. Section 3 describes the hardware infrastructure of CO_2 leakage monitoring equipment and different sensors and modules selected. Section 4 demonstrates the firmware flow of CO_2 remote online monitoring system. In section 5, the implementation and application example is presented. Finally, section 6 is the conclusion of the paper and new avenues for the future works are put forward in this part.

II. Backgrounds

A. Monitoring of CCS Leakage

The effective application of monitoring technologies should ensure the safety of CCS projects, with respect to both human health and the environment, and will contribute greatly to the development of relevant technical approaches for monitoring and verification [4]. Many tools exist or are being developed for monitoring geological CO_2 storage, including well testing and pressure monitoring; tracers and chemical sampling; surface and bore hole seismic; and electromagnetic/geomechanical meters, such as tiltmeters [5].

For example, to monitor the injection of CO_2 into the reservoir of the Sleipner Project in Norway, a project known as the Saline Aquifer CO_2 Storage (SACS) since 1996 [6]. The position of the injected CO_2 in the Utsira reservoir has been identified using 2-D and 3-D seismic time-lapse surveying, a conventional oil industry technique [7]–[8]. At Weyburn, a comprehensive program that included time-lapse 3-D seismic imaging, geochemical sampling and soil gas surveys was used a multifaceted approach to demonstrate effective containment [9]. Surface gas and biological monitoring were carried out in 2009 at the In Salah Gas project (Krechba, Algeria), where geological storage of CO_2 has been underway since mid-2004 [10].

The spatial and temporal resolution of these technologies may not be sufficient for CO_2 migration and surface detection. Further monitoring is conducted by satellite visible light, infrared views with satellite radar and optical aerial photography. Map of CO_2 in the mid-troposphere acquired by the Atmospheric Infrared Sounder instrument (AIRS) on NASA's Aqua satellite during July 2009 [11]. The National Oceanic and Atmospheric Administration (NOAA) ESRL's Global Monitoring Division (GMD) tall tower network provides regionally representative measurements of CO_2 and related gases in the continental boundary layer [12].

However, these techniques focus either on monitoring the work status of CO_2 injection wells and the physical and geo-chemical study of the mechanism of geological structure or on applying high-resolution satellite remote sensing for mapping and acquiring global satellite map of large-scale distribution of CO_2 concentration, which are difficult to accurately locate the source position and time accuracy of CO_2 leaks or to meet the needs of real-time monitoring and early warning of near-surface leakage and migration of small-scale CO_2 geological storage.

B. CO_2 Monitoring Based on Wireless Sensor Networks

WSN is a modern information technology with the integration of sensor technology, automatic control technology, data transmission network, storage, processing and analysis technology [13], [14]. Compared with traditional monitoring techniques, WSN is featured by its low-cost, low power consumption, simple to deploy, without onsite maintenance, etc., and it can achieve a variety of regional low-cost unmanned continuous monitoring [15]. Advances in WSN technology as well as the development of tiny sensor devices enable us to monitor environmental information [16]. WSN have become significant tools for analyzing natural phenomena. Over the past 10 years, a great deal of research effort has been devoted to the development of air environment monitoring based on tiny WSN systems [17]–[22]. Therefore, based on technologies of micro-sensors, GPS, GPRS, to meet the need of leakage monitoring of CO_2 geological storage, this paper developed a remote online monitoring system. The system mainly consists of geological CO_2 leakage monitoring equipment, data center server and the clients, as shown in Figure 1.

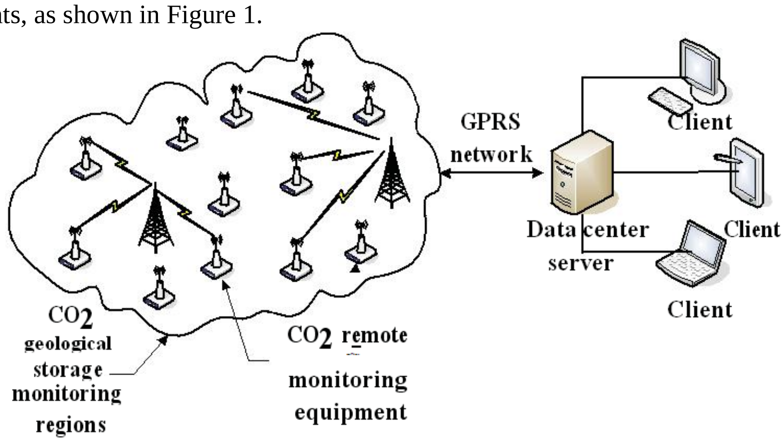


Fig.1. System structure of geological CO_2 leakage monitoring system

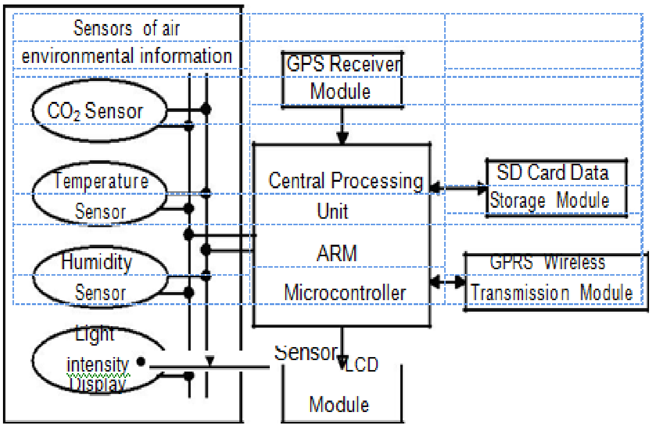


Fig. 2. Hardware infrastructure diagram of geological CO_2 leakage monitor.

The development of CO_2 remote real-time monitoring equipment is the core task of the whole system. The equipment can be deployed in CO_2 geological storage monitoring region. It can collect CO_2 concentration, temperature, humidity, light intensity and other air environmental information through sensors and get the current position (longitude, latitude and elevation) and timing (GMT) information through Global Positioning System (GPS). The General Packet Radio Service (GPRS) network will send the collected data to the data center server, and then simultaneous data query, analysis and monitoring can be achieved on multiple clients.

III. Hardware Infrastructure

Geological CO_2 leakage monitoring equipment based on WSN are mobile devices used by humans. The equipment is composed of the air environment sensors array, GPS receiver module, central processing unit, SD card data storage module, LCD display module and GPRS wireless transmission module, as shown in Figure 2.

A. Microcontroller

The microcontroller (NXP LPC1768 Chip) manages the operation of each module. Its ARM Cortex-M3 based micro-controller for embedded applications featuring a high level of integration and low power consumption.

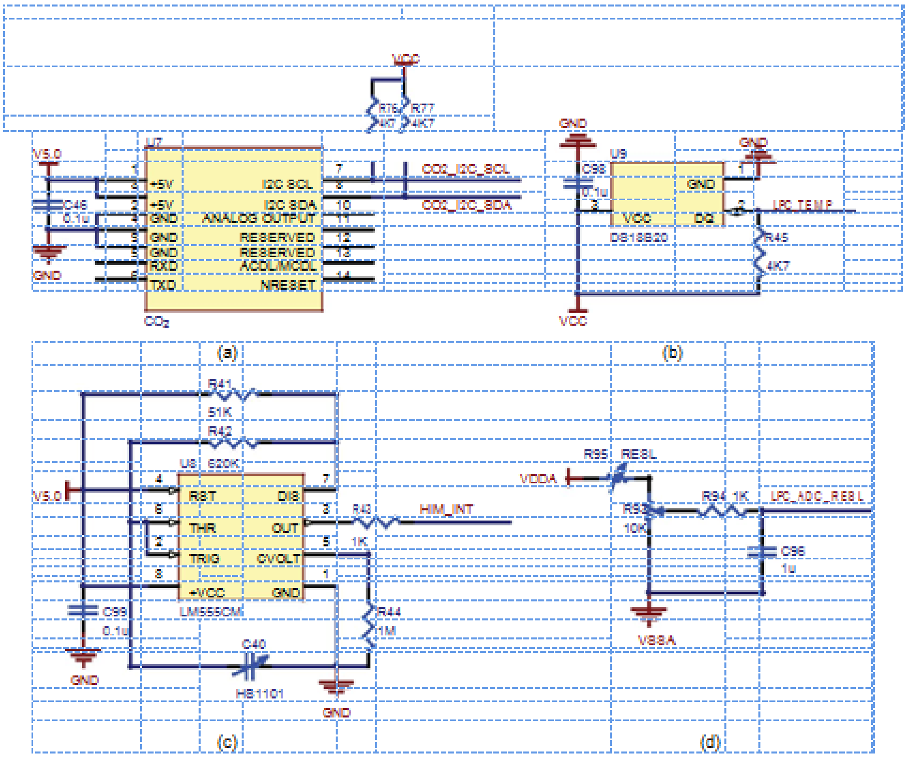


Fig. 3. Circuit diagram of air environment sensor array. (a) NDIR CO_2 sensor. (b) Temperature sensor. (c) Humidity sensor. (d) Light intensity sensor.

The LPC1768 operate at CPU frequencies of up to 100 MHz. The peripheral complement of the LPC1768 includes up to 512 KB of flash memory, up to 64KB of data memory, Ethernet MAC, USB Device/Host/OTG inter-face, 8-channel general purpose DMA controller, 4 UARTs, 2 CAN channels, 2 SSP controllers, SPI interface, 3 I2C-bus interfaces, 8-channel 12-bit ADC, 10-bit DAC, four general purpose timers, 6-output general purpose PWM, ultra-low power Real-Time Clock (RTC) with separate battery supply, and up to 70 general purpose I/O pins.

B. Sensor Specifications and Circuit Design

Air environmental information acquisition sensors array includes: NDIR CO_2 sensor, temperature sensor, humidity sensor, and light intensity sensor. These sensors, respectively, provide real-time collection of air data to the central process-ing unit. Each sensor is described in the following.

NDIR CO_2 Sensor: With broad measurement range, high sensitivity, fast response time, good selectivity and strong anti-interference ability, S-100 miniature CO_2 sensor module is selected [23]. This sensor adopts Non-dispersive infrared °C = degrees Celsius, RH = Relative humidity, ppm = parts per million, s = second.

TABLE I. CO_2 Sensor Specifications [23]

Parameter	Technical Data
Operating Temperature	0 °C～50 °C
Storage Temperature	−30 °C～70 °C
Operating Humidity	0%～95% RH (Non-condensing)
Sensing Method	NDIR (Non-dispersive infrared)
Measurement Range	0～5000 ppm (expandable up to 10000 ppm)
Accuracy	±30 ppm ±5% of measured value
Step Response Time (90%)	60 s
Sampling Interval	3 s

(NDIR) spectroscopic analysis technology, and is widely used in many fields such as air quality monitoring. As shown in Table 1, its performance and accuracy could well meet the needs of geological CO_2 monitoring. The circuit diagram of NDIR CO_2 is as shown in Figure 3(a)

Temperature Sensor: DS1820 digital thermometer, which can convert the temperature to digital within 1second and provide 9-bit digital value of temperature readings is chosen with the measurement range of −55°～ + 125° and value-added volume of 0.5°. Single-mode 1-Wire bus is adopted by this thermometer to connect to the central processing unit and no external components or backup power supply is needed (Figure 3(b)).

Humidity Sensor: HS1101 humidity sensor is used for acquiring humidity sensor data. The measurement range is of 1～99% RH and voltage input of 5 V DC. Capacitor frequency conversion is applied so as to reach the connection to the central processing unit. The circuit diagram of this sensor is as shown in Figure 3(c).
Light Intensity Sensor: Module A/D within the central processing unit is employed to achieve circuit switching and collecting of light intensity and power supply voltage data (Figure 3(d)).

C. GPS Receiver Module

With the high sensitivity, good tracking performance, and high position and speed accuracy in the world, the G593 is selected as the GPS receiver module which providing the best solution. The G593 GPS module can supports up to 210PRN channels, with 66 search channels and 22 simultaneous tracking channels. It supports signal procession of L1 band signals such as GPS C/A and Satellite Based Augmentation Systems (SBAS), including Wide Area Augmentation System (WAAS), global navigation satellite system (EGNOS), and Multi-functional Satellite Augmentation System (MSAS).

D. GPRS Remote Transmission

The transmission of Real-time collected data is via GPRS wireless transmission module–SIM900A. The module takes Surface Mount Technology (SMT) packaged dual GSM/GPRS as solution, the powerful processor ARM9216EJ-S as the core and the International Mobile Equipment Identity (IMEI) code as a unique identifier. It is characterized by the small chip, compact, high reliability and low power consumption.

Central processing unit uses Universal Asynchronous Receiver Transmitter (UART) to reach the connection to GPRS wireless transmission module to further realize wireless transceivers of data collecting.

First, based on Transmission Control Protocol/Internet Pro-tocol (TCP/IP) stack, the central processing unit initialize UART, send the command AT and initialize GPRS wireless transmission module; Second, send the dial command ATD * 97 # to GPRS wireless transmission module and line on after the dial-up succeeds. Then, the central processing unit starts using Point to Point Protocol (PPP) and TCP/IP stack to get the connection to Domain Name System (DNS) servers via GPRS wireless transmission module, domain name get parsed first and then servers get connected, thus establishing point to point communication with remote mobile networks. Finally, the collected data is packed through User Datagram Protocol (UDP) so as to realize wireless transmission.

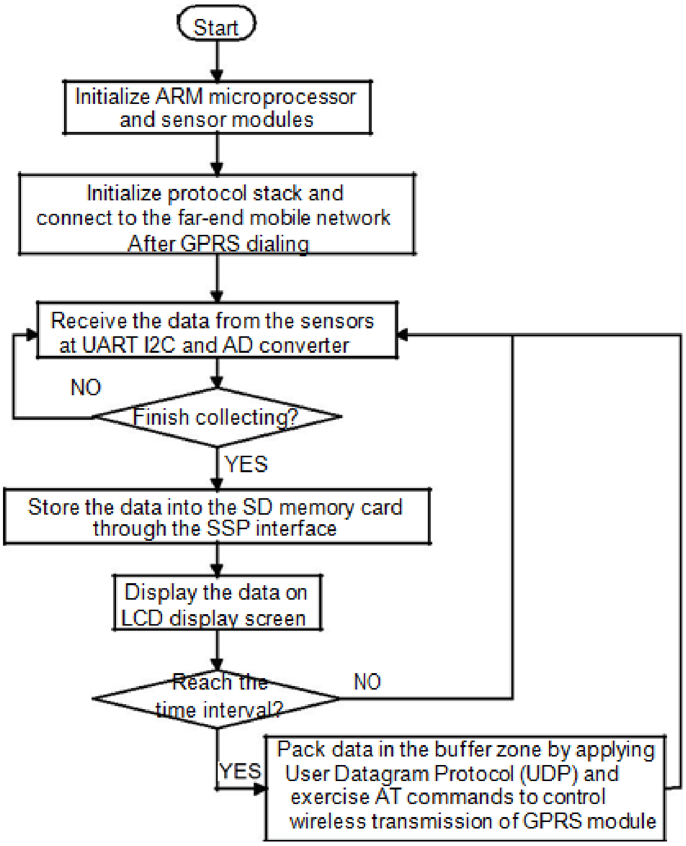


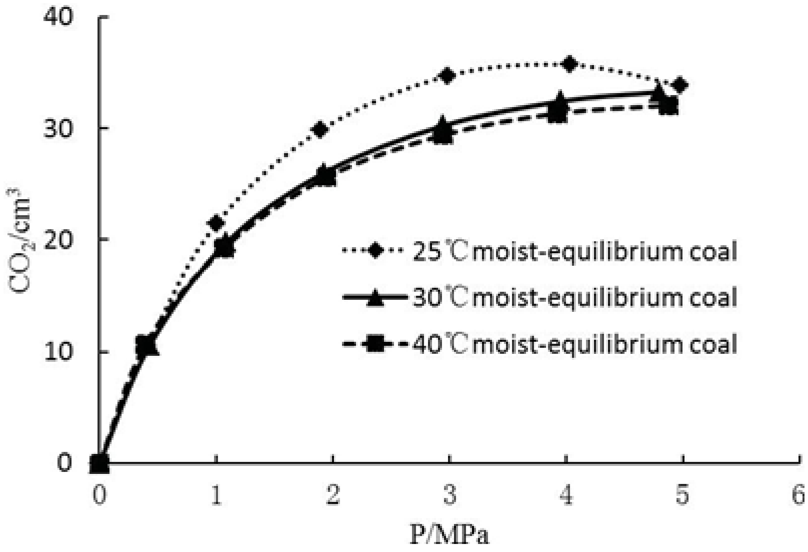
Fig. 4 Firmware flow of CO_2 remote real-time monitoring equipment

IV. Firmware Flow

Firmware process includes two main parts, real-time col lecting and wireless transmission. First, the sensors array of CO_2, temperature, humidity and light intensity are used to collect data; GPS receiver module is adopted to collect GPS position and time information; Afterwards, for the collected data, through GPRS wireless transmission module, continuous wireless transmission is conducted as shown in Figure 4.

Specific procedures are as below:

1) Power the equipment on, then is to initialize the entire CO_2 remote real-time monitoring system, including the circuit initialization of air environment sensors array, central processing unit and all modules. Display the con-trol signal in a fixed time (1 second intervals) and mon-itor the operational status of each module real-timely.
2) After the initialization of TCP/IP protocol stack and the success of dial-up of GPRS wireless transmission module, the central processing unit achieves the connection to remote mobile network and then the point to point communication will be established.
3) Wait for the data of air environmental sensors and GPS receiver module, including CO_2 concentration, temperature, humidity, light intensity, GPS positioning and timing from converters of UART, I2C and A/D.
4) Central processing unit displays the collected data and power supply information on the LCD display module real-timely.
5) When the transmission time interval is reached (interval from 1 second to 30 minutes), pack the stored data according to UDP. The AT commands is applied to control GPRS wireless transmission module to connect to remote wireless communication network and the data packet will be sent wirelessly to a data center server.



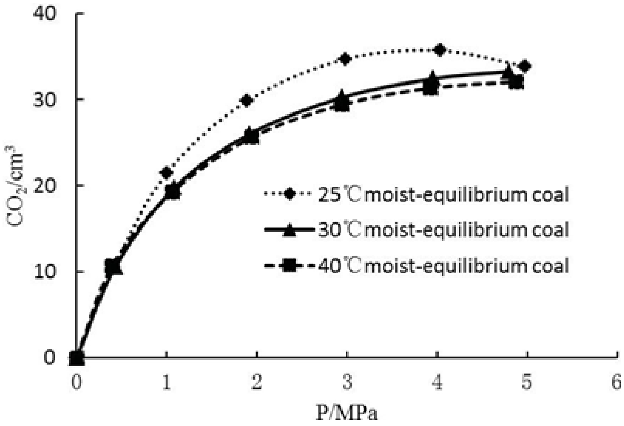


Fig. 6. CO_2 adsorption of moist-equilibrium coal at 25 °C, 30 °C, and 40 °C.

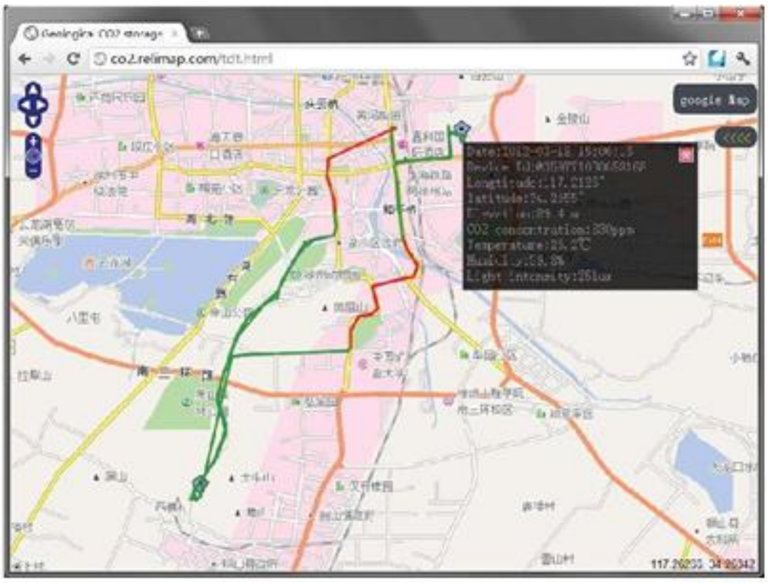


Fig. 7. Geological CO_2 storage and leakage online monitoring WebGIS.

V. Implementation

Remote real-time monitoring equipment for CO_2 Geological Storage and leakage is successfully developed, which can real-ize automatic storage, real-time display and wireless transmit the data of CO_2 concentration, temperature, humidity, light intensity, and GPS positioning and timing.

With size of 6 cm × 12 cm × 18 cm, the weight of monitor-ing equipment is 266 g. It can be easily arranged in a variety of experimental environments for its simple and portable. The implementation of circuit board is as shown in Figure 5.

In fact, the process of CO_2 geological storage can be simpli-fied to be the inverse process of coalbed methane extraction. And the core mechanism is the process of CO_2 adsorption and CH_4 displacement dynamics [2]. So power the equipment on and place it in the experiment of testing the mechanism of action of CO_2 adsorption – analysis in coal seam pore bodies. Respectively monitor the adsorption capacity of the same equilibrium water coal sample at 25, 30, 40°, and the curve of CO_2 adsorption change at different temperatures is acquired, which is as shown in Figure 6.

Figure 6 shows that as the temperature increases, the equilibrium water coal sample needs more gas pressure to adsorb the same amount of CO_2, which further proves that CO_2 adsorption of coal belongs to physical adsorption.

Figure 6 also shows that CO_2 adsorption capacity of the coal sample decreases as the temperature increases, which on the one hand is consistent with the conclusion that the change width of coal surface free energy determines the adsorption capacity of coal surface (as the temperature increases, the free energy of coal decreases) and on the other hand coincides with the fact that the CO_2 adsorption of coal is exothermic. This equipment has effectively measured CO_2 adsorption capacity of equilibrium water coal sample at different temperatures and verified the variation adsorption.

The online monitoring WebGIS was developed using PHP programming language, which running on the Apache web server. For the database, the WebGIS utilizes MySQL because of its speed and reliability. Create, optimize, and deploy stunning cross-browser web maps with the Open Layers. Open Layers is a powerful, community driven, open source, pure JavaScript web-mapping library. With it, we can easily create our own web map mashup using WMS, Google Maps, and a myriad of other map backends [26]. The interface of geological CO_2 storage and leakage online monitoring WebGIS client is shown in Figure 7. Based on the development of the embedded mobile GIS prototype instrument, take Xuzhou city in Jiangsu province, china as an application example, the data collecting and sending terminal whose device ID is 353236012283399 is in wireless transmission at 14:20, May 18, 2012. The device ID (353236012283399) is the unique mobile device identification code (IMEI) obtained from the SIM900A GPRS module, and the current time corresponds to the time reading from the GPS.

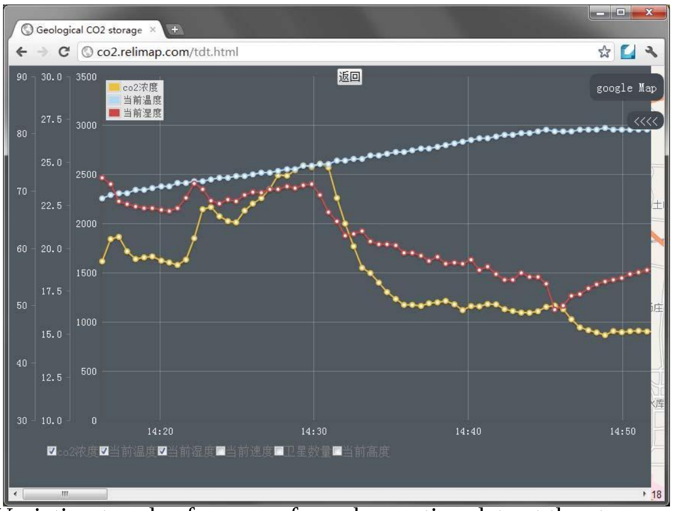


Fig. 8. Variation trends of near-surface observation data at the storage site.

As Figure 8 shows, based on the near-surface observation data at the geological CO_2 storage site from monitoring instrument, the variation trends of CO_2, temperature, humidity and light intensity are analyzed by using of the linear trend analysis.

VI. Conclusion

Based on the sensors of CO_2, temperature, humidity and light intensity, the equipment which is suitable for the surface CO_2 concentration monitoring was developed in order to realize remote real-time acquisition of multivariate information in the monitoring of CO_2 geological storage.

This experiment adopts self-made portable CO_2 monitoring equipment, which obtains localization and time service infor-mation through GPS, and it can cache dynamic changes of real-time monitoring data into SD cards. GPRS is employed to wirelessly transmit them to the server, which ensures the continuity of data acquisition and monitoring.

Apart from the sound effects, the monitoring system is simple in structure, easy to operate, convenient to carry, remote monitoring, automatic storage, real-time display and contin-uous wireless transmission, which provide remote real-time monitoring means for further study of quantitative analysis and dynamic simulation of the process of CO_2 geological storage, leakage, diffusion and migration under complex air environment.

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