WIRELESS MEASUREMENT AND CONTROL SYSTEM OF CARBON DIOXIDE USING INFRARED SENSOR IN GREENHOUSE ENVIRONMENT
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基于红外传感器的温室二氧化碳无线监测和控制系统研制

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ABSTRACT

A carbon dioxide detecting and controlling system has been experimentally established in a greenhouse located in northern China. The developed system consists of several major parts including wireless infrared gas sensor node, wireless receiver and CO_2 concentration controller with pure CO_2 cylinder. The wireless infrared gas sensor was developed for real time detection of CO_2 which is essential for plant photosynthesis. Digitalized data of concentration can be received by the wireless receiver which connects to a laptop installed developed LabVIEW program. Ambient CO_2 concentration can be controlled automatically by the concentration controller based on fuzzy PID algorithm. Experiments demonstrate that the stability fluctuation of detection results is less than 2.2%. The fluctuation of ambient CO_2 concentration under automatic control is less than 60 ppm which proves good efficiency of the system. The proposed CO_2 detecting and controlling system is suitable for precision management of key factors along with temperature, humidity and luminance in greenhouse for optimal production.

摘要

研制了用于温室环境的二氧化碳气体的测控系统。研制的系统主要分为几个部分，包括无线红外检测节点、无线接收器和用于控制二氧化碳气瓶的控制器。二氧化碳作为植物光合作用的重要要素，可以通过研制的无线红外检测节点进行实时检测。检测的浓度信息可以通过数字量的形式无线发送给研制的无线接收器，无线接收器连接温室旁控制室内的电脑，该电脑安装了基于 LabVIEW 平台开发的软件。环境中二氧化碳浓度可以通过模糊 PID 算法由二氧化碳控制器进行调控。实验证明检测结果的波动不大于 2.2%。二氧化碳浓度在设定值范围内波动不超过 60ppm，显示了较好的测控精度。本文提出的二氧化碳测控系统适用于研究温室作物增产和优产，在检测二氧化碳浓度的同时，还可以检测温室内的温度、湿度和光照度。

INTRODUCTION

In recent years, greenhouse has been developed and improved world widely. According to reports, the total area of greenhouse had been increased more than 2 million hm^2 in China *(Jianing et al. 2016; Jianing et al. 2016)*. Meanwhile, the demand of modern technologies and technical equipment are increasingly required in greenhouse environment. Production of greenhouse can be increased and the quality can be optimized by taking advantage of the modern techniques, including sensors, signal transmission, signal processing, and control strategy and algorithm *(Malaver et al. 2015; Serodio et al. 2001; Gutierrez et al. 2014)*. These technologies effectively promote the development of modern greenhouse by quantification of key factors, decreasing the complexity of environment and increase the efficiency of signal processing. Among the applicable techniques, sensors and sensing techniques have been reported by many groups *(Somov et al. 2013; Somov et al. 2014; Salker et al. 2005; Misra et al. 2004)* for achieving accuracy real time detection of key factors in greenhouse. Also, control and management of key factors such as temperature, humidity and luminance in greenhouse have been reported experimentally *(Hwang et al. 2010; Ma et al. 2015)*.

Carbon dioxide is essential for plants photosynthesis and is also studied by many researchers *(Yauda et al. 2012)*. Carbon dioxide concentration can be detected by CO_2 sensors which are developed in different sensing principles *(Ren et al. 2014)*. Detection and fertilization of CO_2 is significant to plant growth management in greenhouse. Compared to traditional sensors, photo-electrical sensors have been reported widely in recent years due to their advantages including high-sensitivity, fast response time, non-intrusive nature, wide sensing range and long lifespan *(Ritobrata et al. 2013; Charles et al. 2014)*. Therefore, photo-electrical CO_2 sensors are adopted in the developed system.

In this paper, a CO_2 detecting and controlling system has been experimentally established along with other key factors including temperature, humidity and luminance. These sensors have been controlled by the developed circuits and are integrated as a sensor node in the system. Considering the wiring difficulty in greenhouse environment, wireless communication has been adopted in the system by using the 433 MHz communication frequency. CO_2 fertilization can be performed by the developed CO_2 controller. Design details of sensor node, CO_2 controller and circuits are introduced firstly. Then, sensing and testing experiments of the system with discussion will be demonstrated.

MATERIALS AND METHODS

System structure

The proposed CO_2 measurement and control system consists of developed software and hardware. The structure diagram is shown in Figure 1. As shown in the figure, the developed sensor node is placed in the greenhouse and it is responsible for sensing key factors including CO_2, luminance, temperature and humidity. The detected data can be transmitted to a developed wireless receiver which connects to a laptop in the adjacent control room by wireless communication. Detected data can be shown and be stored in the laptop. In the greenhouse, there is also a CO_2 controller that is able to control the open/close of a CO_2 cylinder for gas fertilization. The CO_2 controller can be controlled by the sensor node or the laptop by wireless communication. Considering the difficulty of wiring power cables and signal cables in greenhouse environment, wireless communication is desirable for the duty of signal transmission. Besides, water proof of the sensor node is also considered and is performed to avoid circuit damage caused by the moisture condensation in greenhouse.

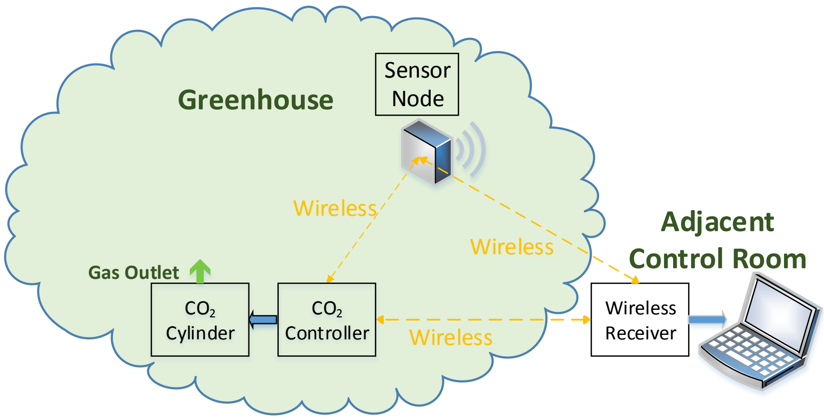

Fig.1 - Structure diagram of the developed system in the greenhouse

Wireless sensor node

The wireless sensor node was developed for monitoring real time ambient factors including CO_2 concentration, temperature, humidity and luminance. The function diagram of the sensor node is shown in Figure 2.

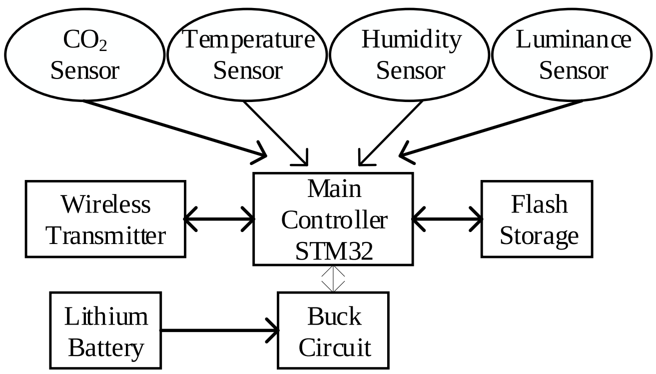

Fig. 2 - Function diagram of the developed sensor node

The main controller is a surface mounted microchip (STM32F103R). It is a 32-bit chip with a maximum CPU speed of 72 MHz. The main controller is responsible for signal processing of the sensor node. It is connected with the individual sensors and a wireless module (Si4463). The circuit is powered by a lithium battery that consists of four serially connected 18650 batteries. A buck circuit board was developed to convert voltage and the output voltage is set as 5 V. The main controller stores data in a 64-M flash chip (W25Q64BV). In order to guarantee the wireless communication quality, an amplifier chip (RFX2401C) was applied to enhance signal strength. Therefore, collected data can be sent to the wireless receiver and the CO_2 controller.

Sensors and signal receiver

The CO_2 sensor applied in this system is a compact infrared sensor based on the Beer-Lambert Law. Compared to the general chemical sensors, it has a larger detection range which is 0 to 10^4 ppm. The sensing precision is about 30 ppm. The photo of CO_2 sensor is shown in Figure 3 (b). The temperature and humidity sensors are combined together and it is shown in Figure 3 (b) as well. It can be buried in the soil to detect the temperature and humidity in underground as shown in Figure 3 (a). It can also detect the ambient air temperature and humidity. The detection accuracy is about 0.5 ℃ of temperature and 1.8% of humidity. The luminance sensor is embedded on the panel of the developed sensor node. This luminance sensor has a low driving current of 0.7 mA and its accuracy is about 0.054 Lux. The three sensors are connected with the main controller of the sensor node.

Wireless communication has been adopted in this system to avoid high expense instalment of telecommunication infrastructures. Wireless communication is flexible, fault-tolerant and simpler to implement in greenhouse. The wireless module is also shown in Figure 2 (b). Compared to WIFI and Bluetooth, the applied 433 MHz communication wireless module has a better penetration that is suitable for the greenhouse environment because the transmission can be guaranteed considering the inevitable plant shelter. This is a key advantage of this signal transmission method in greenhouse environment.

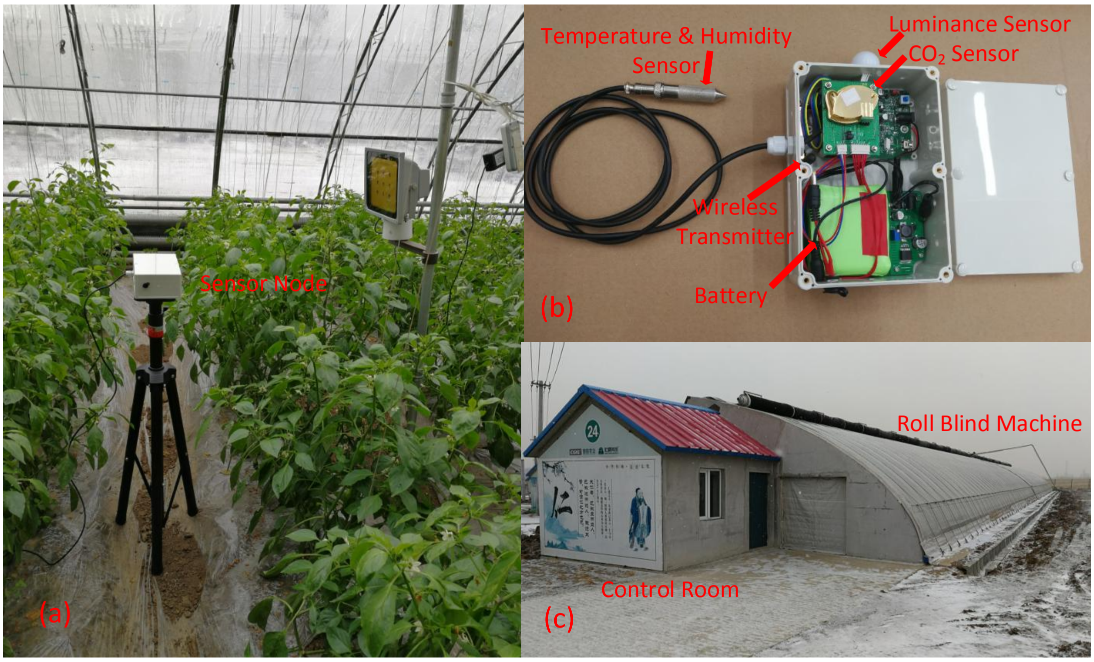

Fig. 3 - Photo of the sensor node working in the greenhouse (a), the inside view of the developed sensor node (b) and the outside view of the greenhouse (c)

Concentration controller and developed software

The CO_2 concentration can be increased to a desired level by a CO_2 controller. It consists of wireless module and an electromagnetic valve (SONGLE). The CO_2 cylinder can be opened by the electromagnetic valve to increase gas concentration. Fuzzy PID algorithm has been adopted in the system to calculate the compensation of CO_2 concentration. The duty circle of driving circuit of the electromagnetic valve is flexible and the minimum switching period is set as 5 seconds.

A monitoring GUI (graphic user interface) based on LabVIEW platform was developed and is shown in Figure 4. The received data can be stored in the laptop and the curve can be shown in separate windows. The detected CO_2 concentration, temperature, humidity and luminance data are sent from the sensor node and can be received by the wireless receiver which is connected to the laptop. The received data can be stored in separately created files in the laptop. These files can be opened by using Excel. As shown in Figure 4, the received data are separately shown in a window with a pull-down menu. The function of choosing sensor nodes has been developed for future experiments that involving multiple developed sensor nodes. The column on the right side of the software is the configuration zone of the serial ports including the communication baud rate, stop bit and byte counting etc.

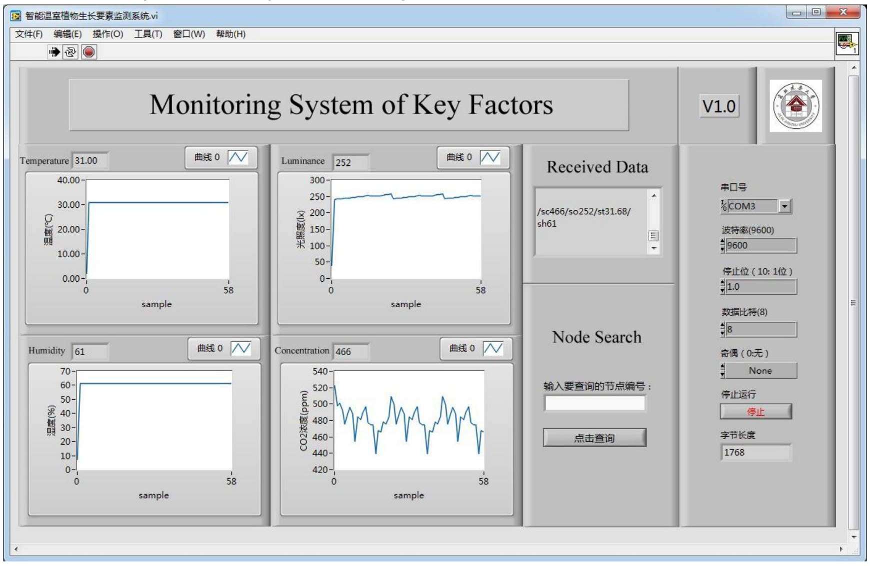

Fig. 4 - Developed monitoring system based on LabVIEW platform

RESULTS

Performance test of gas sensor

The developed sensor node was tested in laboratory in order to evaluate its sensing performance. Standard gas samples were flushed into a gas cell by a mass flow meter. Two standard gas samples of 1000 ppm and 600 ppm were tested separately and the results are shown in Figure 5. In a total period of 1,000 seconds the stability tests were carried out. For the 1000 ppm gas sample, the maximum and minimum detected values were 1017 ppm and 978 ppm respectively. The relative error can be calculated as 2.2%. The fluctuation of detected concentration is slightly smaller for the 600 ppm standard gas sample. The maximum and minimum concentrations are 619 ppm and 584 respectively. The relative error can be obtained as 1.9%. The detected results demonstrated acceptable sensing performance.

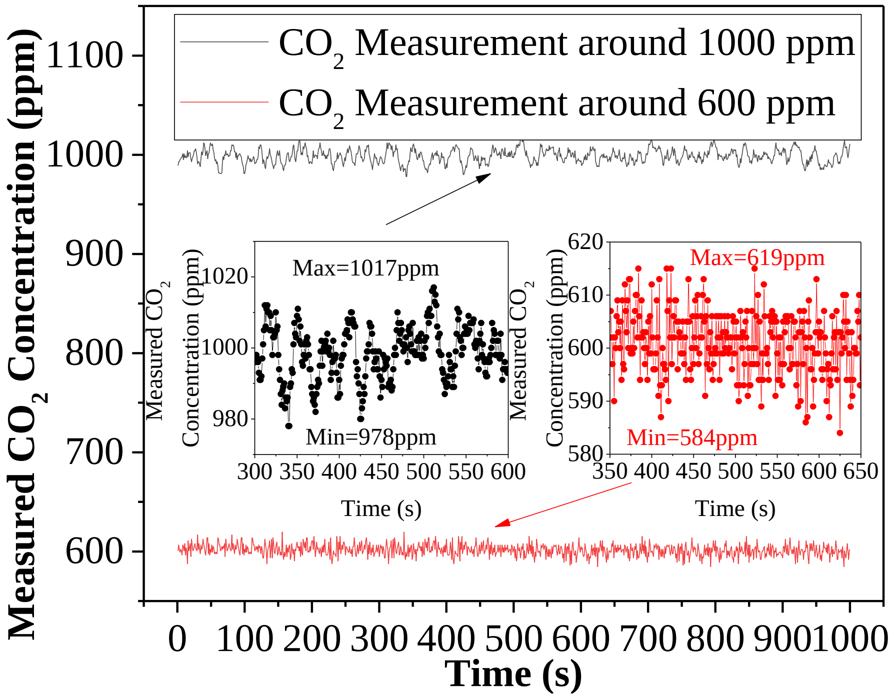

Fig. 5 - Stability tests of the developed sensor node

Wireless network test

The wireless communication tests were carried out in order to evaluate the wireless transmission performance. The greenhouse occupies a total area of 640 m^2. The developed sensor node was placed about 1 m height from ground. The RSSI (received signal strength indication) and package loss rate were measured experimentally and are shown in Figure 6 (a) and Figure 6 (b). As shown in Figure 6 (a), the RSSI value decreases with the increasing of the distance. The RSSI value is in the range from -25 dBm to -60 dBm when the distance between the sensor node and the wireless receiver is less than 20 meters. Then, the RSSI value slowly decreases with the increase of the distance. The RSSI value located in the range from -80 dBm to -90 dBm when the distance increased to 80 -100 m. As shown in Figure 6 (a), the main trend of RSSI value is decreasing while the distance is increased. Then, the package loss rate was tested as shown in Figure 6 (b). It can be seen that the package loss rate remains zero while the distance increases from 0 m to 28 m between the sender, which is the sensor node, and the receiver. Then, the package loss rate increases with the increase of the distance. The loss rate reaches about 2.1% when the distance is 80 meters. If the sent data is not correctly received, the sender will send again until the receiver successfully captures the data and answers the sender. This process not only wastes time but also consumes more power which will shorten the usage time of the battery. From the experiments, the RSSI value and package loss rate demonstrate that the wireless communication is reliable and suitable for the developed system.

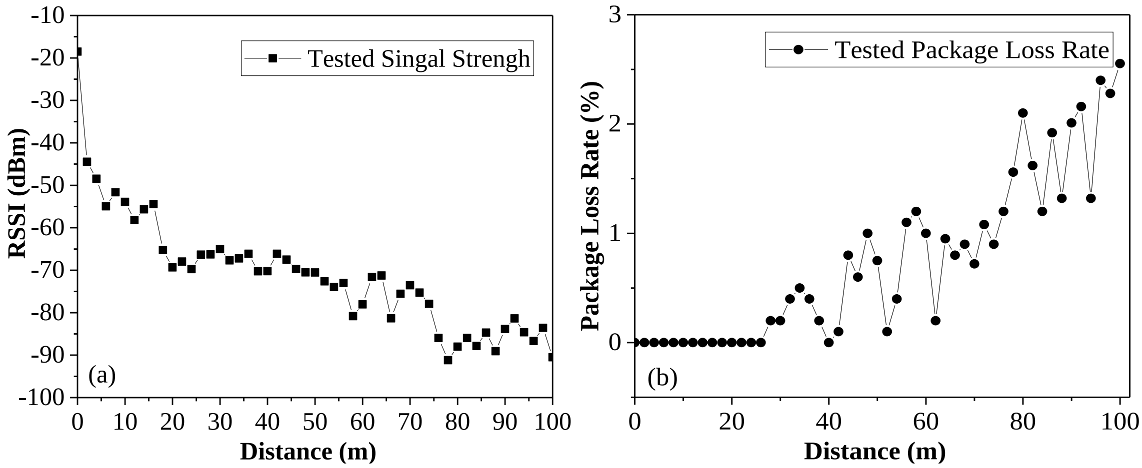

Fig. 6 - Tests of RSSI (a) and package loss rate (b) for the wireless communication in greenhouse

Concentration measurement

The developed system was deployed in a greenhouse with the length of 80 meters. The sensor node, CO_2 controller and CO_2 cylinder were placed in the greenhouse. The laptop was located in the adjacent control room which is shown in Figure 3 (c). A 24-hours detection experiment was carried out as shown in Figure 7. In Figure 7, it can be seen that the CO_2 concentration and temperature in the greenhouse were detected as shown. The CO_2 concentration was detected every 30 seconds from 12:00 at noon and the experiment ends at 11:59:30 the next day.

The CO_2 concentration decreases from the beginning of the experiment due to the photosynthesis effect. In a photosynthesis process, CO_2 is absorbed by the plants and is converted into chemical energy. In this way, CO_2 can be realised as an important fuel of plants. As shown in Figure 7, the CO_2 concentration decreases from 300 ppm at 12:00 to 130 ppm at 3:30. It is essential to realise that the roll blind machine for greenhouse starts to work at about 3:30 for thermal insulation because the outside of the greenhouse gets dark. The surface of greenhouse that faces towards the sun is covered at about 3:30. Therefore, the photosynthesis process in the greenhouse is dramatically slowed and the decrease of CO_2 concentration is interrupted. Then, the CO_2 concentration starts to increase because the greenhouse cannot be entirely sealed. The CO_2 concentration increases due to the air exchange between the inside and outside of the greenhouse. The increase will be continued until the roll blind machine rolls up the covering the next morning. Then, the CO_2 concentration starts to fall again caused by the photosynthesis.

It can be seen that CO_2 concentration is in a circulation in the total 24-hours experiments. This is caused by the resist of air-exchange by the greenhouse which is good for warm keeping. In Figure 7, the temperature is shown as the red curve. It can be seen that the trend of the temperature and CO_2 concentration is opposite. The temperature in the greenhouse increases in the process of photosynthesis due to the strong sunshine. The temperature starts to decrease at 3:30 when the rolling blind machine cover the surface of the greenhouse. Without the heating effect of sunshine, the temperature decreases continually until the roll blind machine rolls up the covering the next morning. According to the experiment, it can be realized that the CO_2 concentration fertilization is necessary to compensate the concentration drop caused by photosynthesis and air-exchange resist of the greenhouse. Therefore, a reasonable CO_2 fertilization is desired to compensate the CO_2 concentration which is important for photosynthesis.

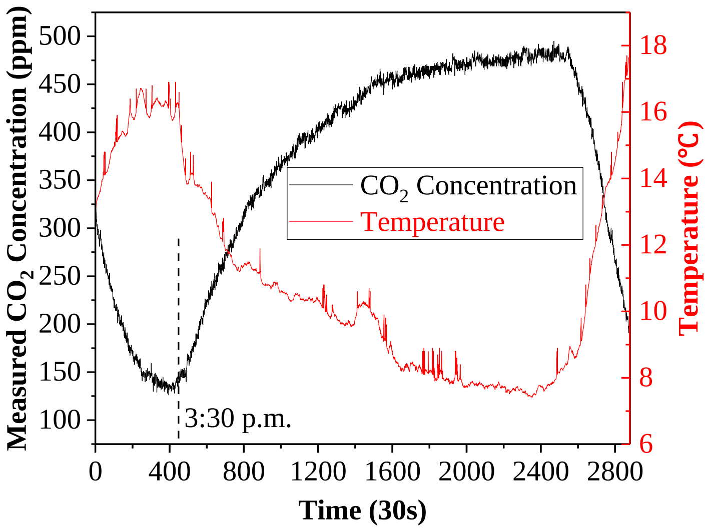

Fig. 7 - Detection of CO_2 concentration and temperature in the greenhouse in a period of 24 hours

The humidity and luminance tests were also carried out by using the developed system. The humidity decreases in the photosynthesis process as shown in Figure 8 (a). The humidity in the greenhouse increases and remains at a high level in the night. Its peak value can be 89% during the night. On the other side, the luminance in the greenhouse is affected by the roll blind machine directly as shown in Figure 8 (b). During the period when the greenhouse is covered, the luminance drops to zero in the figure. It can be seen that the machine rolls up the covering at about 7:00 a.m. because the luminance value starts to increase in the figure. The luminance value dramatically raises when the sunshine covers the greenhouse. The humidity and luminance are both impacted by human activities and can be controlled to a large extent. The luminance can be supplied by artificial light source in the night and the related experiments will be carried out in the future studies.

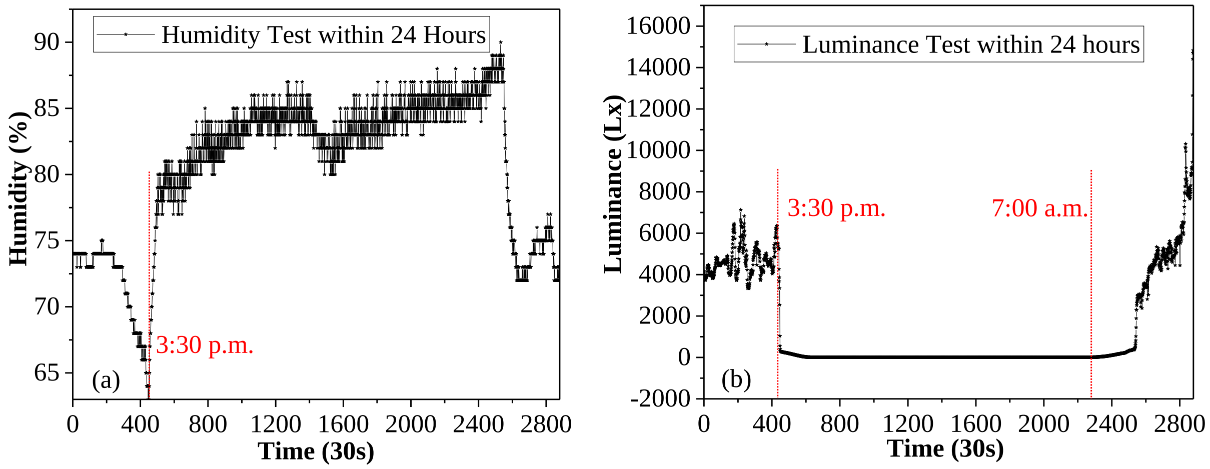

Fig. 8 - Detection of humidity (a) and luminance (b) in the greenhouse in a period of 24 hours

Test of CO_2 concentration control

The CO_2 compensation experiment was carried out to evaluate the control performance of the developed system. The results are show in Figure 9. As shown in the figure, the total experimental period can be divided into four parts from T0 to T3. In the first period of time, T0, the CO_2 concentration remains at a constant level of about 690 ppm without photosynthesis. Then, the CO_2 concentration starts to decrease in the T1 period due to the photosynthesis effect. In this stage, the CO_2 cylinder is closed and the concentration is without control or human impact. After setting a target concentration at 1000 ppm, the CO_2 cylinder is opened by the electromagnetic valve via wireless control. The pure CO_2 gas slowly permeate in the greenhouse in the T2 period. It can be seen from the figure that the most fluctuated period lasts approximately 1 hour. This period of time can be shortened by setting a larger flow speed of the CO_2 cylinder or adjusting the PID control strategy. Finally, the CO_2 concentration remains constant around 1000 ppm which is the target point in the T3 period. The maximum fluctuation of concentration is less than 60 ppm. It can be seen that the CO_2 concentration can be effectively regulated by the system during the period from T0 to T3.

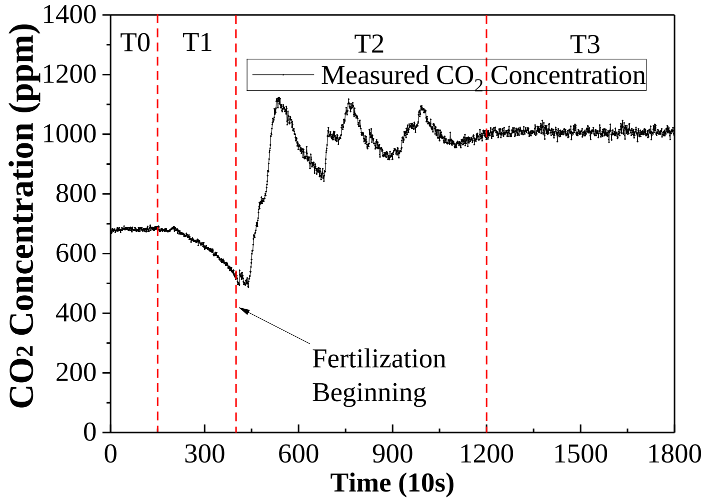

Fig.9 - Experiment of CO_2 concentration control in the greenhouse at 1000 ppm

CONCLUSIONS

A carbon dioxide detecting and controlling system has been proposed. This system has been experimentally applied in a greenhouse in northern China. The developed system consists of several major parts including a sensor node, a wireless receiver and a CO_2 concentration controller with pure CO_2 cylinder. The sensor node is wireless communicated with other parts and an infrared CO_2 sensor is embedded in it. The wireless infrared gas sensor was developed for real-time CO_2 detection which is essential for plant photosynthesis. Collected data of concentration can be received by the wireless receiver which connects to a laptop installed developed LabVIEW program. In the greenhouse, CO_2 concentration can be controlled automatically by the concentration controller based on fuzzy PID algorithm. According to the experiments, the fluctuation of detection results is less than 2.2%. The fluctuation of CO_2 concentration under automatic control in the greenhouse is less than 60 ppm which proves good performance of the system. In addition, the proposed CO_2 detecting and controlling system is also capable to detect temperature, humidity and luminance in the greenhouse. The proposed system can be applied for researching optimal production in greenhouse environment. Multiple sensor nodes will be studied in the future in order to be applied in larger greenhouses.

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