DESIGN AND TEST OF REAL-TIME MONITORING SYSTEM FOR NON-CONTACT FERTILIZATION FLOW

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非接触施肥流量实时监测系统的设计与试验

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ABSTRACT

Precision fertilization is one of the important links in the precision agricultural operation system. In recent years, the demand for precision fertilization in facility greenhouse has become more and more urgent. As such, this paper designs an accurate and practical fertilization on-line monitoring system. The system adopts capacitance conversion chip PCAP01 and SCM STM32F103C8T6 to build a capacitance detection circuit. The effective acquisition of differential capacitance sensor microcapacitor signal output under this system is realized. The response relationship between the mass flow and the sensor capacitance output was studied, and a linear fitting model of fertilization was established. According to the prediction, the model determination coefficient was 0.9997. The experiment shows that the system has good adaptability to ambient temperature. The average measurement error is 1.13%, which meets the technical requirements of flow measurement. The capacitive fertilization online measurement system provides an effective way for the on-line acquisition of fertilization flow. It is of great significance for the implementation of high-precision variable fertilization.

摘要

精准施肥是精准农业运营体系中的重要环节之一。近年来，人们对设施温室精准施肥的需求越来越迫切。本文主要设计了一套准确实用的施肥在线监测系统。系统采用电容转换芯片 PCAP01 和单片机 STM32F103C8T6 搭建电容检测电路，实现了差分电容传感器微电容信号输出的有效采集。研究了质量流量与传感器电容输出的响应关系，建立了线性拟合模型。模型确定系数为0.9997，并通过预测验证了模型。实验表明，该系统对环境温度具有良好的适应性，平均测量误差为 1.13%，可以满足流量技术要求。电容式施肥量在线测量系统为施肥机施肥流量的在线获取提供了有效途径，对实现高精度变量施肥作业具有重要意义。

INTRODUCTION

Excessive application of chemical fertilizer has become one of the important factors leading to agricultural non-point source pollution (*Huang, 2016; Hou, 2015; Qi et al, 2016; Zhang et al, 2006*). Precise variable fertilization technologies can apply fertilizer as needed as needed, so as to improve the utilization rate of fertilizer and reduce water and soil pollution (*Yuan et al, 2016; Kuş, 2021*). The online measurement of fertilizer application is critical for high precision variable fertilization (*Dan et al, 2021; Song, 2012*). The biggest difficulty is the complex characteristics of fertilization and non-contact measurement without destroying the drain pipe. The research on online monitoring of the seeding rate of precision seeders is relatively mature (*Wang, 2013; Zhou, 2013; Cheng, 2012; Zhang and Zhao, 2013; Liu, 2013; Wang et al, 2013)*. However, the online measurement of the mass flow of solid particle fertilizer is less. The main measurement methods are the weighing method, indirect measurement of fertilizer discharge axis and the photoelectric method. *Peng and Wei, (2012),* designed a belt-scale-based fertilization test device to measure the flow at the fertilizer discharge port and the fertilizer application rate per unit area.

Zhao et al., (2010), used the dynamic weighing method to obtain the mass flow rate of fertilizer. Combined with location information, the rational application of fertilizer based on spatial distribution was realized.

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Maet al., (2015), applied the Hall sensors and encoders to measure the rotation cycle and angle of the fertilizer discharge shaft indirectly. This method has simple structure, but the measurement error is relatively large. Some scholars used the photoelectric method to measure the fertilizer flow rate online. *Swisheret al., (2002),* adopted the laser light source, and transmitted the light through a trapezoidal light chamber to the array detection unit with 32 photodiodes. According to the shading intensity of granular fertilizers, the instantaneous flow rate of fertilizers in the air-transported fertilizer machine was obtained. *Griftet al., (2001),* studied the relationship model between the output pulse width of the near-infrared photodetector and the fertilizer flow rate. Under laboratory conditions, the accuracy of the photoelectric flow sensor at different flow rates and densities was realized. *Backet al., (2014),* used the CCD camera to obtain the falling image of the fertilizer particles. Through the image recognition method, the diameter and quantity of fertilizer particles were obtained. Combined with the fertilizer density, the online monitoring of the mass flow rate of fertilizer discharge was realized. The photoelectric imaging method has high measurement accuracy, but it is easily affected by the fertilizer powder covering the probe. The measurement results are poor.

In this paper, an on-line measurement method of fertilizer mass flow rate based on the principle of capacitance detection is presented. A differential capacitive fertilizer flow sensor is designed, and an on-line measurement system of fertilization is constructed. Using nitrogen, phosphorus and potassium fertilizers commonly used in agriculture, the relationship model between fertilizer flow and capacitance response was established and verified. The measurement and display of fertilizer application and the whole-process monitoring of fertilizer pipe clogging were realized.

MATERIALS AND METHODS

MECHANICAL STRUCTURE OF THE FERTILIZER APPLICATOR AND THE PRINCIPLE OF FERTILIZERATION DETECTION

Fertilizer applicator is mainly composed of fertilizer box, fertilizer application device, transmission bearing, controller, soil covering device, press wheel, rotating chain, press spring and seed row box, as shown in Figure 1.

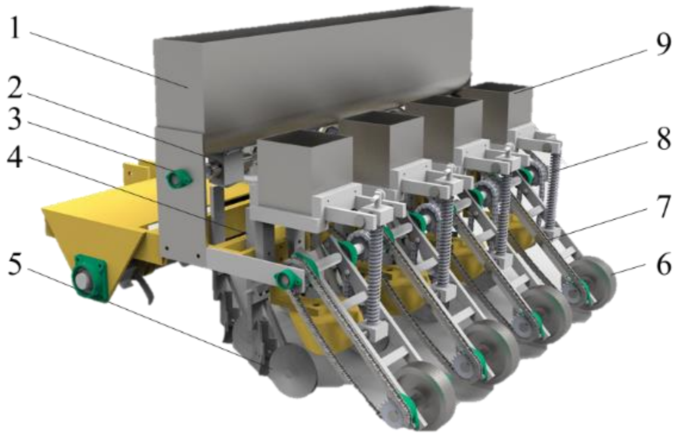

Fig. 1 - Mechanical structure diagram of the fertilizer applicator
1. Fertilizer box; 2. Fertilizer discharger; 3. Transmission bearing; 4.Controller; 5. Press wheel; 6. Ground wheel; 7. Rotary chain; 8. Press spring; 9. Seed metering box

Before using the fertilizer applicator, the sensor needs to be calibrated. Relevant parameters of the machine are calibrated and entered into the database of the circuit control module. Then, the fertilization of the fields is also input into the circuit control module. The fertilizer spreader is driven by an engine and a speed sensor is installed on the driving wheel. The sensor monitors the moving speed of the fertilizer applicator in real time, and transmits the speed information to the circuit control module. The circuit control module analyzes the data, calculates the rotational pulse frequency of the stepping motor and transmits it to the driver. The stepping motor is driven to control the rotational speed of the transmission shaft. Quantitative chemical fertilizer will ensure that it is deeply applied in the fertilizer ditch, so as to achieve quantitative and accurate fertilization.

During the normal operation of the fertilizer applicator, the fertilizer falls freely in the closed fertilizer pipe. Due to different dielectric constants of fertilizer and air, the equivalent dielectric constant of the material between the plates will change. When the fertilizer falls through the capacitor plate, it causes a change in the output capacitance. At this time, the change of the sensor output capacitance is:

$$\Delta C = C - C_0 = \frac{s\,(\varepsilon_1 - \varepsilon_2)}{\rho_1 dV} m_1 \tag{1}$$

where ΔC is the capacitance change when the fertilizer passes through the sensor, F; S is the plate area, m^2; ε_1 is the dielectric constant of the fertilizer, F/m; ε_2 is the air dielectric constant, F/m; ρ_1 is the fertilizer density, kg/m^3; D is the plate spacing, m; V is the detection field volume between the plates of the capacitive sensor, m^3, and m_1 is the mass of fertilizer in the sensor, kg.

On the basis of obtaining fertilizer flow rate, the amount of fertilizer per unit area can be further obtained according to the working width and advancing speed of the fertilizer applicator.

$$M(t) = \frac{Q(t)}{DV(t)} \tag{2}$$

where $M(t)$ is the fertilizer applied per unit area, kg/m^2; D is the operation width of the fertilization machine and tool, m; $V(t)$ is the forward speed of the machine and tool, m/s; $Q(t)$ is the mass flow rate of the fertilizer, kg/s.

CONSTRUCTION OF SENSOR TEST SYSTEM

The online detection system of fertilizer amount is mainly composed of capacitive fertilizer flow sensor, forward speed sensor and vehicle-mounted terminal, as shown in Figure 2.

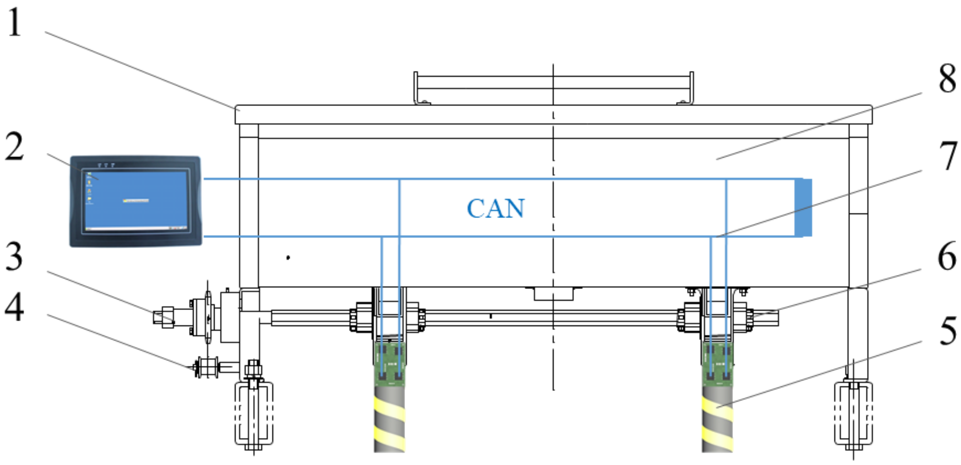

Fig. 2 - Structure diagram of fertilizer application quantity detection system
1. Frame; 2. Vehicle display terminal; 3. Transmission shaft; 4. Speed sensor;
5. Flow sensor; 6. Fertilizer exhauster; 7. CAN bus; 8. Fertilizer box

The system adopts the Controller Area Network (CAN) bus structure, which can realize the distributed on-line detection of each fertilization pipeline and facilitate the node expansion of fertilizer applicators with different widths. The capacitive fertilizer flow sensor is installed on the fertilizer discharge disk to obtain the online mass flow rate of fertilizer. The forward speed sensor is located on the forward wheel to obtain the forward speed of the machine and tools. The on-board terminal is located in the cab. It can receive the real-time information through the built-in CAN bus adaptation module, and display the fertilizer after information processing. In addition, the fertilizer flow sensor can judge the clogging state of the pipeline according to the state of fertilizer, and display the alarm state through the alarm light on the sensor.

TYPES AND SELECTION OF FERTILIZER DRAINERS

The commonly used fertilizer dischargers include external groove wheel fertilizer dischargers, planetary wheel fertilizer dischargers and spiral fertilizer dischargers. Sheave spreaders are especially common in seeding spreaders because of their simple structure and easy cleaning. When the outer groove wheel fertilizer discharger works, the groove wheel rotates with the rotation of the fertilizer discharge shaft. The fertilizer is filled in the groove wheel and accompanied by the rotation of the wheel. The outermost layer of fertilizer is discharged from the sheave box by friction and conveyed to the fertilizer ditch through the discharge pipe. The fertilizer can be adjusted by adjusting the effective working length of the sheave, which can be used for fertilizer removal in different working environments.

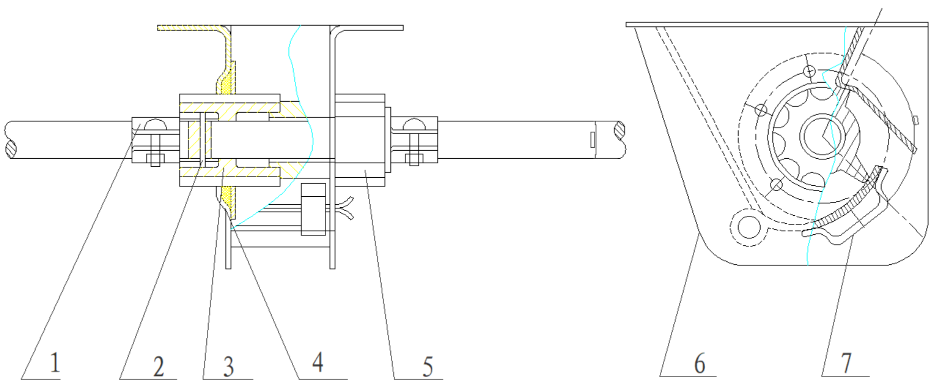

Fig. 3 - External grooved wheel fertilizer spreader
1. Clamp; 2. Shaft pin; 3.Fertilizer wheel; 4.Taper pin; 5. Block box; 6. Fertilizer box; 7. Fertilizer tongue

STRUCTURAL DESIGN OF THE FLOW SENSOR

According to the preliminary experimental results, the structure of the fertilizer flow sensor has been improved this year, mainly focusing on the systematic improvement of the sensor from the plate structure and overall IP protection. The new fertilizer flow sensor adopts the spiral plate structure, and the internal fertilizer guide tube is made by 3D printing.

In order to ensure the consistency of the structure parameters of the spiral plate, the guide plate is directly designed and pasted on the guide tube, so that the guide plate is pasted along the guide structure. In addition, PCB mounting table is designed on the fertilizer guide tube and connected to the plate by short thread. The integrated design of capacitor plate, PCB board and fertilizer guide tube can reduce the influence of stray capacitance on the test results.

In order to realize the IP67 protection design of the sensor, the shell is processed by CNC (Computerized Numerical Control Machine) as a whole. Meanwhile, the sealing groove is designed on the upper and lower end cover, and the sealing ring is matched to meet the protection requirements.

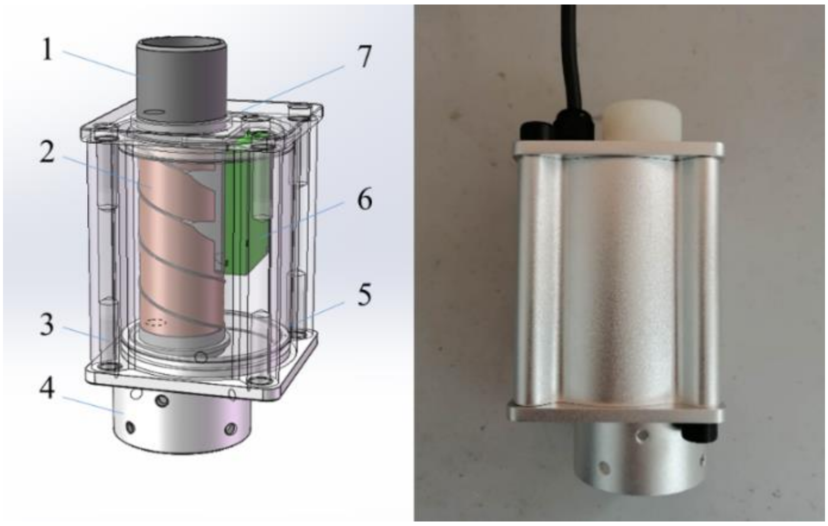

Fig. 4 - Structure diagram and physical object of flow sensor of the screw fertilizer
1. Fertilizer input pipe; 2. Spiral capacitance plate; 3. Fixing bolt; 4. Fertilizer output pipe;
5. Alloy housing; 6. PCB circuit board; 7. Fixed bushing;

MICROCAPACITOR SIGNAL CONDITIONING CIRCUIT

Capacitor signal conditioning circuit is the key to obtain high-precision capacitor signals. The commonly used microcapacitor detection circuit mainly includes a DC charge-discharge conversion circuit, an AC capacitive conversion circuit, and a microcapacitor detection circuit based on capacitor digital conversion (*Zhou et al, 2010; Jin et al, 2019; Jin et al, 2020; Jin et al, 2018; Zhou et al, 2017; Bergeijka et al, 2001; Zhou et al, 2014*). Among them, the capacitive digital conversion method based on integrated detection chip is widely used (*Bai et al, 2020; Xiong et al, 2020*).

When the fertilizer passes through the capacitive sensor, the capacitance change is 0.1pF. In order to ensure the accuracy and reliability of the measurement, this paper uses the capacitance-to-digital conversion method to design the conditioning circuit of the sensor. The capacitive-to-digital conversion chip PCAP01 and the microcontroller STM32F103C8T6 were used to form a microcapacitor signal measurement circuit.

PCAP01 is a capacitance-to-digital conversion chip launched by German ACAM Company with DSP processing unit, which is specially used for microcapacitor measurement. The TDC conversion module and environmental compensation function are integrated on the chip, with the highest measurement precision and frequency up to 6aF and 500 kHz, respectively. Furthermore, the protocol control pin IIC_EN of PCAP01 is grounded and SPI transmission mode is selected. In order to eliminate the influence of environmental factors on the measurement results as much as possible, PCAP01 takes the ratio of the sensor capacitance to the reference capacitance as the calculation result. The measurement result is output as a 24bit digital signal, which is convenient for subsequent conversion processing. Since the measurement result of PCAP01 is the output ratio relative to the reference capacitance, the measurement result needs to be converted.

The conversion formula is as follows:

$$C = \frac{C_{mear}}{2^{21}} \times C_{ref} \tag{3}$$

where C is the measured capacitance after conversion, pF; C_{mear} is the measured output ratio, dimensionless; C_{ref} is the reference capacitance value, pF.

When the electrode plate of the fertilizer flow sensor is connected to PCAP01, the drift connection mode is adopted. Electrode plate 1 is connected to PC2; electrode plate 2 is connected to PC3, and electrode plate 3 is connected to PC4. At the same time, the ceramic capacitors of the same order of magnitude as the basic capacitance of the sensor are connected to PC0 and PC1 as the reference capacitances.

SIGNAL ACQUISITION AND PROCESSING

The vehicle-mounted terminal is the hardware platform for the software operation of the fertilizer rate detection system. It is responsible for receiving the information and forward speed of each sensor in real time, so as to complete the calculation and statistics of the fertilizer rate at each pipeline. Taking the X86 architecture based Atom motherboard as the core, the terminal integrates the solid state storage module, data communication module, LIQUID crystal display and input and output module. The real-time data on the bus is obtained through the built-in USB-CAN communication adaption module. The terminal can be well compatible with Windows operating system, and is convenient for the development of upper computer software.

Under the Keil MDK software development environment, C language is used to write part of the software MCU (Microcontroller Unit). The software design adopts the modular programming method, and its functions mainly include system initialization, PCAP01 firmware writing CAN module initialization, capacitor data acquisition and preprocessing. Its program flow is shown in Figure 5.

After the system is on, the single-chip microcomputer executes the initialization program to complete the configuration of each IO port. After that, the firmware information of internal EEPROM is read, and the SRAM region inside PCAP01 is written through SPI bus to enter the configuration state of PCAP01, where the sampling rate is configured at 10kHz and the blocking alarm threshold is 0.5PF. When the capacitance measurement is completed, the MCU reads the results of PCAP01 to obtain the capacitance information. On the one hand, the data is sent to the on-board terminal through CAN bus, and the real-time capacitance is compared with the blocking threshold. Once the blocking threshold is exceeded, the corresponding IO port is driven by MCU, so that the alarm indicator light is always on to realize the local alarm.

The upper computer software was developed by LabWindows/CVI 2012 of National Instrument (NI). Lab windows software adopts interactive programming technology and integrates powerful function library and graphical interface control, which is suitable for the development of measurement and control system. The software functions of the developed fertilizer rate detection system mainly include communication parameter setting, system operation, data processing, data display and playback.

The software interface is shown in Figure 5.

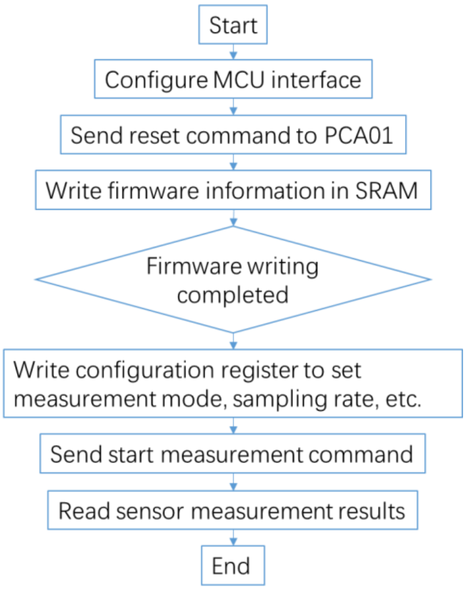

Fig. 5 - Flow chart of MCU software program

After the software receives the real-time data sent by the sensor through CAN bus, the capacitance value is calculated and the filtering algorithm is used to filter the acquired original capacitance. According to the pre-calibrated capacitor-mass flow signal, the mass flow rate of fertilizer in the drainage tube is obtained. In order to ensure the real-time performance of data acquisition and display, multi-thread method is adopted to carry out data acquisition, processing and display. The main thread is used to create, display and run the interface. The data acquisition thread is used to complete capacitor information acquisition and data processing, and the display thread is used to complete the display and playback of all data.

Granular fertilizer and compound fertilizer N-P commonly used in agriculture were used in the experiment ${}_2O_5$-K_2.The ratio of O content is 24-14-9, and the fertilizer particles are uniform without agglomeration. In order to check the reliability and accuracy of the capacitive fertilizer rate sensor, the fertilizer rate measurement experiment was carried out on the fertilization test bench. The test bed was mainly composed of fertilizer box, fertilizer discharge shaft, servo motor, reducer and fertilizer discharge pipe. The test bed was driven by a servo motor to rotate the fertilizer discharging shaft. The input voltage of the analog quantity under the speed control mode of the servo motor can be changed by the upper computer to realize the automatic control of the motor speed. Then the speed of the fertilizer discharging shaft can be continuously adjusted to achieve on-line adjustment.

RESULTS

INFLUENCE OF TEMPERATURE ON FERTILIZER FLOW SENSOR

Ambient temperature is one of the important factors affecting the performance of the capacitance sensor. Considering the field working environment of the detection system, the temperature of the fertilizer rate sensor was tested in the range of 15-55^{o}C.

First, the test sensor was put into the thermostatic control box (type 202FBX-0, Shanghai Lishu Instrument Co., LTD., ±1^{o}C). Then the measurement system was started and preheated for 5 min to enter the detection state after the measurement data was stable. Taking 5^{o}C as the change gradient, the temperature inside the temperature control box was adjusted to 55^{o}C. After each adjustment, wait for 5min after the temperature display was stable. The detected and reference capacitances and the current actual temperature were recorded, and the influence relationship between the differential capacitance (the difference between the detected and reference capacitance) and the temperature were obtained. The test results are shown in Figure 6.

From Figure 6, when the temperature gradually rises from 15^{o}C to 55^{o}C, the difference between the sensor and its zero-base capacitance increases from 0.02 pF to 0.33 pF. Compared with the initial value of the detection capacitance, the change rate is close to 8%. However, the difference between the detection and reference capacitances is always in the range of 0-0.019 pF. This indicates that differential capacitance sensing can effectively improve the influence of ambient temperature on the measurement, which is conductive to improving the accuracy of measurement.

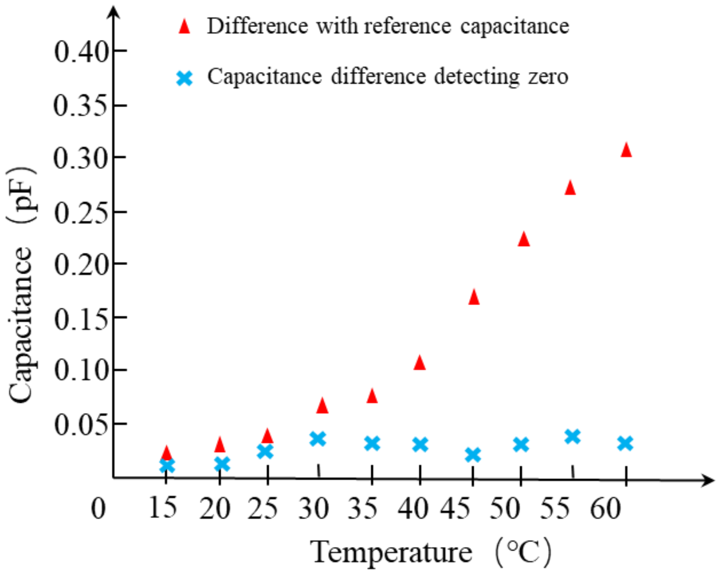

Fig. 6 - Influence of temperature on capacitance output

INFLUENCE OF FERTILIZATION ON THE FERTILIZER FLOW SENSOR

A feeding box is placed at the fertilizer outlet of the measuring device, and the sensor calibration is carried out by the weighing method. The rotation speed of the fertilizer discharging shaft was set at 20 r/min. The rotation time of the fertilizer discharging shaft was controlled by the upper computer to obtain different fertilizer discharge according at different operation time. After each fertilizer discharge, an electronic balance (SL4001, Shanghai Minqiao Electronic Instrument Factory, 4000±0.1 g) was used to weigh the fertilizer in the receptacle. The cumulative capacitance value of the difference between the measured and reference capacitance sensors was recorded at the same time. Calibration tests were performed for each fertilization by the Matlab software. The response curve of fertilizer mass and capacitance value was obtained as shown in Figure 7.

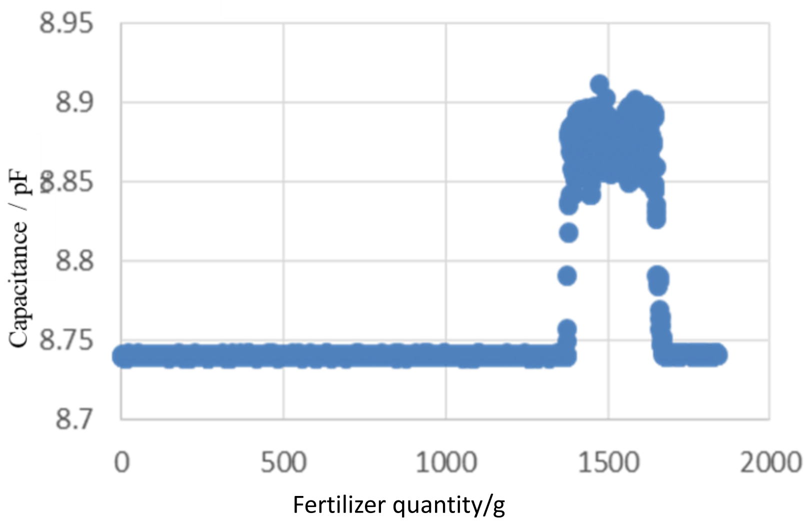

Fig. 7 - Signal response of the compound fertilizer passing through the sensor

It can be seen that when the fertilizer passes through the sensor, its capacitance value will change from 8.75 pF to 8.87 pF. Through linear fitting and normalization, the relationship model between capacitance and mass obtained is as follows:

$$Q(t) = 20.644C(t) + 2.6815 \tag{4}$$

It can be seen that there is a linear relationship between the capacitive output value of the granular fertilizer flow sensor and the fertilizer application. With the increase of fertilizer application, the capacitive output will increase correspondingly, and the coefficient determined by the model is R^2=0.9997.

VERIFICATION OF THE FERTILIZATION TESTING SYSTEM

In order to verify the accuracy of the fertilization test system under different discharge speed, the system was tested at Shengfa Family farm in Dubolan Town, Qingdao from September 18 to 20, 2020.

Fig. 8 - The developed prototype of granular fertilizer flow sensor

In order to verify the accuracy of the fertilization detection system under different discharge flows, the rotating speed of the fertilizer discharging shaft was set as 15 r/min, 21 r/min, 27 r/min and 31 r/min, respectively. A feeding dish was placed under the discharge port to compare the measured value of the fertilizer obtained by the detection system with the actual weighing value of the fertilizer in the receiving dish. The results are shown in Table 1.

Table 1

Test results of the fertilization detection system

Rotation rate (r/min)	Measuring mass (g)	Real mass (g)	Relative error (%)
15	849.2919	864	1.70
	857.756	857	0.09
	345.5783	333	3.78
	643.2648	642	0.20
21	766.0966	776	1.28
	949.4153	961	1.21
	1424.021	1417	0.50
	1799.742	1786	0.77
27	1232.238	1231	0.10
	328.2374	327	0.38
	906.4758	913	0.71
	1919.064	1928	0.46
31	663.4959	650	2.08
	1223.774	1201	1.90
	2191.152	2157	1.58
	1901.723	1875	1.43

It can be seen from Table 1 that the system can accurately measure the fertilizer under different speed of fertilizer discharge. The average measurement error is 1.13%, which meets the actual requirements. Therefore, it is feasible to measure the fertilizer online by the capacitance method.

CONCLUSIONS

1) In this paper, a differential capacitive fertilizer flow sensor based on ring pipelines was designed. A micro-capacitance detection circuit composed of STM32F103C8T6 and PCAP01 was built, and a fertilizer amount detection system based on LabWindows/CVI was constructed to realize the online detection of fertilizer.

2) The response relationship between the mass flow and the sensor capacitance output was studied. The linear fitting models of three fertilizers were established, and the model determination coefficients were 0.9889, 0.9898 and 0.9935, respectively. Moreover, the model was predicted and verified.

3) The test shows that the fertilization detection system has good adaptability to the environmental temperature. It can accurately measure the fertilization and timely alarm the failure of the fertilizer pipe clogging. The maximum measurement error of the fertilization was 3.75%, which can meet the actual production needs.

This paper mainly discusses the feasibility of using capacitive sensing method to measure the fertilizer online. Currently, the moisture content of fertilizers when leaving the factory is required to be no more than 1%. Therefore, the influence of changes in the moisture content of fertilizer on the sensor is not considered in the preliminary test. In the actual production, the condensation and agglomeration of fertilizer will occur, indicating that the moisture content will change to a certain extent. In the future work, the change of moisture content of fertilizer and the influence of environmental humidity on the sensor measurement should be considered to improve the adaptability of the detection system.

ACKNOWLEDGEMENT

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