Review of Sensors for Greenhouse Climate Monitoring

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***Abstract*—A greenhouse provides shelter and protects plants from harsh environment and external interferences. It allows plants to grow under an optimum condition which maximizes the growth potential of the plants. The existing systems only allow for the monitoring of climate variables such as temperature or humidity and often overlook many other important factors such as CO_2, light, soil moisture, soil temperature etc. Neglecting these climate factors leads to inaccurate observation of the overall greenhouse climate condition. To make up for this weakness, the prototype designed for this particular research will allow better monitoring of the climate condition in a greenhouse by integrating several sensor elements such as CO_2, temperature, humidity, light, soil moisture and soil temperature into the system. The purpose of this paper is to provide a review of a range of popular sensors on the market. The paper also discusses their operating principles as well as addresses their advantages and disadvantages. Experiments were carried to test the accuracy of the sensors and the results indicate that the sensors used in this project are relatively accurate and have good stability.**

Keywords- Humidity sensor, temperature sensor, light sensor, CO_2 sensor, moisture sensor, environmental monitoring.

I. INTRODUCTION

A greenhouse allows the growers to produce plants in places where the climate would otherwise be unfeasible to grow them. It makes plant cultivation independent of the geographic location or the time of the year. It also provides shelter for the plants, protects them from harsh weather conditions, insects and diseases. It allows plants to grow under an optimum condition, which maximizes the growth potential of the plants.

Various environmental factors influence the quality and productivity of plant growth. Continuous monitoring of these environmental parameters gives valuable information to the grower to better understand how each factor affects the quality and the rate of plant growth, and how to maximise crop yield. Several research teams are engaged in greenhouse monitoring using wireless sensor networks. [1-5]

Work has been undertaken in our laboratories to design and develop a prototype of a wireless control network for environmental monitoring and management of a commercial greenhouse [6]. Experiments have been set up to test the feasibility and reliability of the system. The system is able to monitor up to six environmental parameters. The environmental parameters that this project focuses on are:

- Atmospheric Temperature
- Humidity
- Carbon Dioxide (CO_2)
- Light Intensity
- Soil Moisture

In this paper we review a range of commercially available sensors and address their relative merits and demerits. A handful of sensors have been evaluated in the laboratory. The paper is arranged as follows: Section 2 presents a survey and evaluation of sensors; Section 3 gives an overview of the sensor station which has been designed and implemented; Section 4 presents discussion and evaluations of the selected sensors; Section 5 presents the experimental results of a few sensors and Section 6 will present the conclusions and recommendations.

II. REVIEW AND EVALUATION OF SENSORS

Sensor technologies have made an enormous impact on the modern day industries. There are thousands of sensors available on the market ready to be attached to a wireless sensing platform. In this particular section of the paper we look at some of the sensor technologies that are available and can be used for monitoring the parameters of a greenhouse. We also discuss their operating principles and make comments on their advantages and disadvantages.

A. Atmospheric Temperature Sensing Technology

Temperature sensing technology is one of the most widely used sensing technologies in the world of sensors. It allows for the measurement of temperature in various applications and provides protection from excessive temperature excursions. Five different families of temperature sensors are available on the market. Each family of temperature sensors has its advantages and disadvantages. Depending on the application, one sensor may be more suitable than the other.

1) *Thermocouples*

A thermocouple is a junction between two wires of dissimilar metals. The point of contact between the wires generates a voltage that is proportional to the temperature. Thermocouples are suitable for measuring over a large temperature range, up to 2300 °C [7]. They are less suitable for applications where smaller temperature differences need to be measured with high accuracy. For such applications thermistors and resistance temperature detectors are more suitable. Applications include temperature measurement for kilns, gas turbine exhaust, diesel engines, and other industrial processes.

Figure 1. Thermocouples

Advantages: wide temperature range (200°C - 1300°C), relatively cheap, highly accurate, minimal long-term drift and fast response time.

Disadvantages: the relationship between the temperature and the thermocouple's output signal is not linear, low output signal (mV), vulnerable to corrosion, and calibration of thermocouples can be tedious and difficult.

2) *Resistance Temperature Detectors (RTD)*

RTDs are widely used in many industrial applications such as air conditioning, food processing, textile production, processing of plastics, micro-electronics, and exhaust gas temperature measurement. RTDs are basically temperature sensitive resistor devices. The resistance increases with temperature. Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core [7].

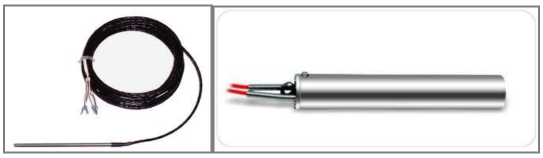

Figure 2. Resistance Temperature Detectors

Advantages: Linear over a wide temperature range, relatively accurate, good stability and repeatability at high temperature (65-700°C)

Disadvantages: low sensitivity, higher cost than thermocouples and vulnerable to shock and vibration

3) *Thermistors*

Similar to RTDs, thermistors are also temperature dependent resistor devices. Thermistors are not as accurate or stable as RTDs but they are easier to wire, cost less and almost all automation panels accept them directly. Thermistors are made of semiconductor materials with a resistivity that is especially sensitive to temperature [7].

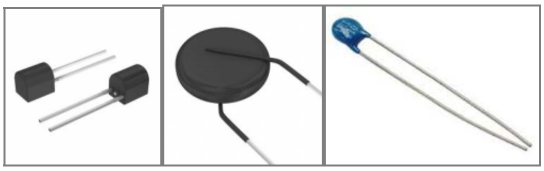

Figure 3. Thermistors

Advantages: highly sensitive, low cost, accurate over small temperature range and good stability

Disadvantages: non-linear resistance-temperature characteristics, self heating and limited temperature operating range

4) *Integrated Circuit (IC) Temperature sensors*

In low cost applications most of the sensors stated above are either expensive or require additional circuits or components to be used. However Integrated Circuit (IC) temperature sensors are complete, silicon-based sensing circuits with either analogue or digital output. IC temperature sensors are often used in applications where the accuracy demand is low.

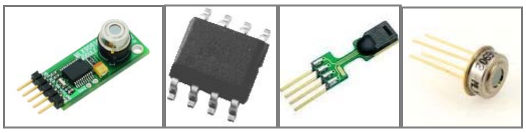

Figure 4. IC Temperature Sensors

Advantages: low cost, excellent linearity and easy-to-read output.

Disadvantages: limited temperature range, self heating, fragile and slightly less accurate when compared to other types.

B. *Humidity Sensing Technology*

When it comes to humidity sensing technology, there are three types of humidity sensors: capacitive, resistive and thermal conductivity humidity sensors.

1) *Capacitive Humidity Sensors (CHSs)*

Capacitive Humidity Sensors (CHSs) are widely used in industrial, commercial, and weather telemetry applications. CHSs consist of a substrate on which a thin film of polymer or metal oxide is deposited between two conductive electrodes. The sensing surface is coated with a porous metal electrode to protect it from contamination and exposure to condensation [8]. The substrate is typically glass, ceramic, or silicon. The changes in the dielectric constant of a CHS are nearly directly proportional to the relative humidity of the surrounding environment.

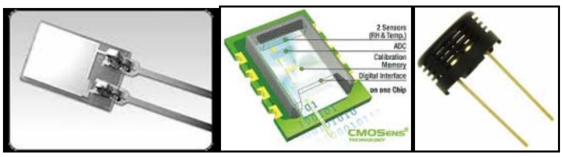

Figure 5. Capacitive Humidity Sensors

Advantages: able to function in high temperature environments (up to 200°C), near linear voltage output, wide RH (Relative Humidity) range, high condensation tolerance, reasonable resistance to chemical vapours and contaminants, minimal long-term drift, high accuracy, small size and low cost

Disadvantages**:** limited sensing distance and sensor interface can be tedious and difficult.

2) Resistive Humidity Sensors (RHSs)

Resistive Humidity Sensors (RHSs) measure the changes in electrical impedance of a hygroscopic medium such as conductive polymer, salt, or treated substrate [8]. These sensors are suitable for use in control and display products for industrial, commercial, and residential applications. RHS consists of noble metal electrodes either deposited on a substrate by photo resist techniques or wire-wound electrodes on a plastic or glass cylinder.

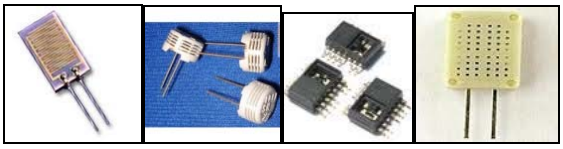

Figure 6. Resistive Humidity Sensors

Advantages: faster response time than CHSs, near linear voltage output, high accuracy, small size, low cost and wide RH range

Disadvantages: lower operating temperature when compared to CHSs, sensitive to chemical vapours, low tolerance against contaminants and low condensation tolerance.

3) Thermal Conductivity Humidity Sensors (TCHSs)

Thermal Conductivity Humidity Sensors (TCHSs) measure the absolute humidity by quantifying the difference between the thermal conductivity of dry air and that of air containing water vapours [8]. These sensors are suitable for applications such as kilns for drying wood; machinery for drying textiles, paper, and chemical solids; pharmaceutical production; cooking; and food dehydration. TCHS consists of two matched negative temperature coefficient (NTC) thermistor elements in a bridge circuit; one is hermetically encapsulated in dry nitrogen and the other is exposed to the environment.

Figure 7. Thermal Conductivity Humidity Sensors

Advantages: very durable, able to operate in high temperature environments (up to 600°C), excellent immunity to many chemical and physical contaminants, high accuracy, and high condensation tolerance.

Disadvantages: responds to any gas that has thermal properties different from those of dry nitrogen; this will affect the measurements.

C. Soil Moisture Sensing Technology

Excessive moisture is undesirable in agriculture, houses, textiles, packaging materials, electronic appliances, dry food process, etc. Moisture detection is important in a number of different situations. For example, measurement of soil moisture is useful for minimising the amount of irrigation water applied to grow plants and for optimizing plant growth. Excess moisture also creates 'wet feet' in plants and destroys them. Because of the importance of the moisture content of materials, various techniques have been developed to measure it. This sub-section outlines a number of soil moisture detection technologies that are available on the market and lists their advantages and disadvantages.

1) Frequency Domain Reflectometry (FDR) Soil Moisture Sensor

Frequency Domain Reflectometry is *s*ometimes referred to as capacitance sensor. Soil sensor probes that use the Frequency Domain Reflectometry method of soil moisture measurement employ an oscillator to generate an electromagnetic signal that is propagated through the unit and into the soil. Part of this signal will be reflected back to the unit by the soil. This reflected wave is measured by the FDR probe, telling the user what the water content of the soil is [9].

Figure 8. Frequency Domain Reflectometry Soil Moisture Sensors

Advantages**:** highly accurate, fast response time and inexpensive

Disadvantages**:** need to be calibrated for the type of soil they will be buried in.

2) Time Domain Reflectometry (TDR) Soil Moisture Sensor

Time Domain Reflectometry (TDR) sensors propagate a pulse down a line into the soil, which is terminated at the end by a probe with wave guides [9]. TDR systems measure water content of the soil by measuring how long it takes the pulse to come back.

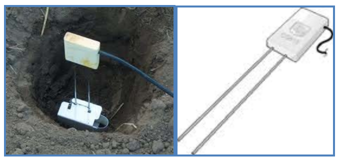

Figure 9. Time Domain Reflectometry Soil Moisture Sensors

Advantages: highly accurate and fast response

Disadvantages: calibration can be tedious, difficult and expensive.

3) *Gypsum Blocks*

Gypsum blocks use two electrodes placed into a small block of gypsum to measure soil water tension. Wires connected to the electrodes are connected to either a portable hand-held reader or a data logger. The amount of water in the soil is determined by the electrical resistance between the two electrodes within the gypsum block. More water present in the soil will reduce the resistance, while less water will increase it.

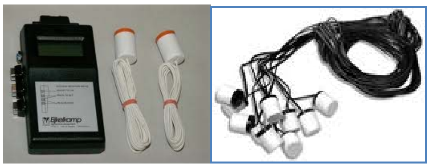

Figure 10. Gypsum Blocks

Advantages: inexpensive and easy to install

Disadvantages: have to be replaced periodically and sensitive to the saline content of water.

4) *Neutron Probes*

Using neutron probes is another way to measure soil moisture content. A probe which is inserted in the ground emits low-level radiation in the form of neutrons. These neutrons collide with the hydrogen atoms contained in water, which is detected by the probe [9]. More the water content in the soil, the more neutrons are scattered back at the device.

Figure 11. Neutron Probes

Advantages: very accurate and fast response

Disadvantages: expensive and users have to be registered with the government due to radioactive elements used to emit the neutrons.

D. *Carbon Dioxide Sensing Technology*

Measuring carbon dioxide is important in monitoring indoor air quality and many industrial processes. Two types of CO_2 detectors are available to measure the CO_2 level in the surrounding environment - Electrochemical CO_2 Sensors and Non-dispersive Infrared (NDIR) CO_2 Sensors.

1) *Electrochemical CO_2 Sensors*

The CO_2 sensitive element consists of a solid electrolyte formed between two electrodes, together with a heater substrate. By monitoring the changes in the electromotive force (EMF) generated between the two electrodes, it is possible to measure CO_2 gas concentration.

Figure 12. Electrochemical CO_2 Sensors

Advantages: Cheap, accurate, real-time sensing, high tolerance against contaminants and small in size.

Disadvantages**:** require a significant amount of power because they operate at high temperature

2) *Non-dispersive Infrared (NDIR) CO_2 Sensors*

NDIR sensors are spectroscopic sensors to detect CO_2 in a gaseous environment by its absorption characteristics. The key components are an infrared source, a light tube, an interference (wavelength) filter, and an infrared detector. The gas is pumped or diffused into the light tube and the electronics measures the absorption of the characteristic wavelength of light.

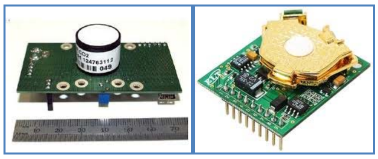

Figure 13. Non-dispersive Infrared CO_2 Sensors

Advantages: high speed, real-time sensing, low power consumption, high contamination tolerance and small in size.

Disadvantages: carbon monoxide often coexists with CO_2 and absorbs a similar wave-length range as CO_2 which results in inaccurate readings. They are also very expensive.

E. *Light Sensing Technology*

Light from the sun is responsible for nearly all life on the earth. Sunlight fuels the process of photosynthesis where plants convert carbon dioxide and water into carbohydrates [10]. Plants use light in the range of 400 to 700 nanometres. This range is most commonly referred to as PAR (photo-synthetically active radiation). Monitoring PAR is important to ensure that plants are receiving adequate light for photosynthesis. Typical applications include forest canopies, greenhouse monitoring etc. PAR is also measured to estimate evaporation in bodies of water, as it plays a key role in surface water temperature. This sub-section will present some of the popular light sensors on the market that can be used for environmental monitoring applications.

1) *Photometric Sensors*

Figure 14. Photometric Sensors

Photometric sensors measure visible radiation or light as seen by the human eye.

Advantages: highly sensitive, good stability, fast response time (10us), low temperature dependency, excellent linearity and small size

Disadvantages: expensive and these sensors are mostly used to measure indoor lighting conditions. For environmental applications, PAR and Solar Radiation sensor are preferred.

2) *Light Dependent Resistor (LDR)*

Similar to photometric sensors, LDRs measure visible light as seen by the human eye. A LDR is basically a resistor; the internal resistance increases or decreases dependent on the level of light intensity impinging on the surface of the sensor.

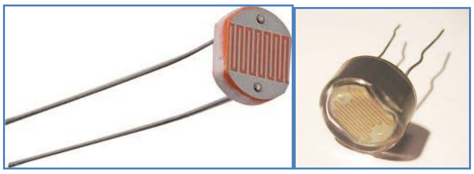

Figure 15. Light Dependent Resistors

Advantages: very cheap, fast response, linear output, and small in size.

Disadvantages: like photometric sensors, LDRs are mostly used to measure indoor lighting conditions.

3) *Pyranometers*

Pyranometers measure total solar radiation. These sensors are commonly used for agriculture, meteorology and solar energy applications. The sensor is composed of a silicon photovoltaic detector mounted in a miniature head [11]. The sensor output current is directly proportional to the level of solar radiation.

Figure 16. Pyranometers

Advantages: highly accurate, excellent linearity, good stability and fast response time.

Disadvantages: bulky and expensive

4) *Quantum Sensors*

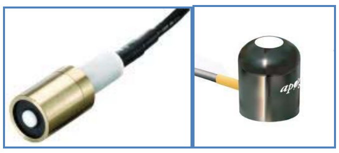

Figure 17. Quantun Sensors

Quantum sensors measure the photosynthetic photon flux density (PPFD) of photosynthetically active radiation (PAR) [11]. They are one of the most popular types of light sensors used in agriculture and environmental industries.

Advantages: very sensitive, fast response, highly accurate, excellent linearity, good stability and small in size.

Disadvantages: expensive

III. OVERVIEW OF SENSOR STATION

A greenhouse sensor station has been designed and fabricated which is part of a complete greenhouse management system. The sensor station takes charge of collecting climate measurements data in a greenhouse (temperature, humidity, CO_2, soil moisture/temperature and light) and transmits the data to a coordinator station. The block diagram of the sensor station is shown in figure 18. The various sensors used in the station are briefly described here.

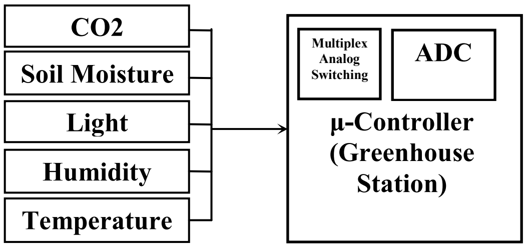

Figure 18. Block diagram of the sensor station

The data acquisition unit consists of five commercial sensors:

- SHT75 humidity and temperature sensors are Sensirion's family of relative humidity and temperature sensors. These sensors integrate sensor elements together with signal-processing in a compact format and provide a fully calibrated digital output [12]. They have humidity operating range from 0 – 100% and temperature operating range from -40 – 125°C. SHT75 sensors have low power consumption and fast response time.
- TGS4161 CO_2 sensors are solid electrolyte CO_2 sensors which exhibit a linear relationship between the changes in voltage output and the CO_2 gas concentration on a logarithmic scale. They have low power consumption, good long term stability and excellent durability against humidity, making them ideal for indoor air control applications such as this project.
- VG400 soil moisture sensors are low frequency soil moisture sensors with low power consumption. Their output voltage is proportional to the moisture content in the soil. The VG400 sensors are insensitive to salinity, small in size and are water proof, making them ideal for both indoor and outdoor applications.
- THERM200 soil temperature sensors are similar to VG400 in terms of low power consumption and robust to external interferences. These sensors have temperature span from -40 to 85°C. The output voltage

is linearly proportional to the change in the temperature of the soil.

- NORP12 light dependent resistance sensor has a spectral response similar to the human eye. Its internal resistance increases or decreases depending on the level of light intensity impinging on the surface of the sensor.

IV. Discussion and Evaluatrion

Humidity, temperature, light and carbon dioxide are the four most common climate variables that growers generally pay attention to. However, looking at these four variables only does not give the growers sufficient information on the greenhouse climate. Other parameters, such as soil moisture and soil temperature, are required to be measured in order to achieve better results. Previous researches have used sensors such as leaf wetness sensors and leaf temperature sensors. These methods were found to be impractical as the wetness of plant leaves varies from one leaf to another and by the location of the plant in the green house. Also, several different types of plants are usually grown in the same greenhouse and different plants have different leaf texture as well as surface geometry. These factors could greatly affect the distribution of water on the leaf surface resulting in inaccurate observations. Many growers and researchers often overlook the fact that the soil conditions also play an important role in the quality and rate of the plant growth. For better absorption and transportation of nutrients into the plant, the soil temperature and soil moisture are required to be maintained within a specific range. Therefore soil temperature and soil moisture were measured along with other climate variables namely, ambient temperature, relative humidity, light and carbon dioxide (CO_2).

This particular application has low accuracy demands; therefore highly accurate temperature and humidity sensors are not necessary. SHT75 IC humidity and temperature sensors were chosen for this application. The most attractive feature that this sensor has is the ability to measure both humidity and temperature. The low cost factor, excellent linearity and small size allow it to be used in almost any application. The only down side of using these sensors is the interfacing problem. The interface provided is proprietary and could be tedious and difficult to program.

Electrochemical CO_2 sensors were found to be ideal for this research as they are cheap and moderately accurate. Out of all the electrochemical CO_2 sensors on the market, TGS4161sensors from Figaro Inc were found to be the cheapest, most accurate and had the lowest power consumption when compared to the others of the same type. However, they are power inefficient especially when they are used in a system which is running off battery power.

VG400 Soil moisture sensor and THERM200 soil temperature sensor were both purchased from Vegetronix Inc. In comparison to other sensors of the same type, these sensors are far cheaper, superior in terms of power consumption, linearity and durability, and are made solely to measure the temperature and moisture content of the soil. Therefore these sensors are ideal for this particular work.

A wide variety of light sensors are available for different applications. Therefore a careful selection of light sensors is essential. Plants absorb sun light and use it to fuel the process of photosynthesis. Sunlight in the range of 400 to 700 nm is normally used by plants and is often referred to as Photo-synthetically Active Radiation or PAR. Monitoring PAR is important to ensure that the plants receive adequate light for photosynthesis. Pyranometers and quantum sensors are best suited for measuring sun light. However, these sensors are very expensive. LDR sensors were found to be the cheapest option available compared to photometric sensors. NOPR12 sensor was chosen for this research because their spectral response is approximately from 380 to 740 nm, which is within the PAR range. However, for precision agriculture applications, it is preferred to use quantum sensors or pyranometers.

V. Experimental Results

A. *Experimental Setup*

Experiments were carried out to test the accuracy of each sensor used in the sensor station. THERM200 and VG400 sensors were tested in a garden. The area for testing was a 1m x 1m patch of soil. Two sensors of each type were placed next to each other and were tested at 30 different locations within the testing area. The reason for placing the sensors close to each other is to minimise any unexpected variances.

SHT75, NORP12 and TGS4161 were all tested in an electronics lab. Two sensors of each type were placed close to each other and measurement samples were taken for an hour at intervals of 5 minutes. The results obtained from the experiments are presented in the next sub-section (figures 19 to 24)

B. *Results*

This sub-section presents the results obtained from the experiments done with each sensor.

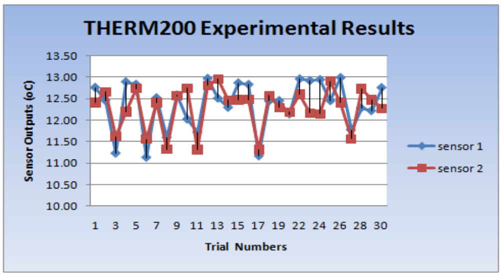

Figure 19. THERM200 experimental results (Soil Temperature)

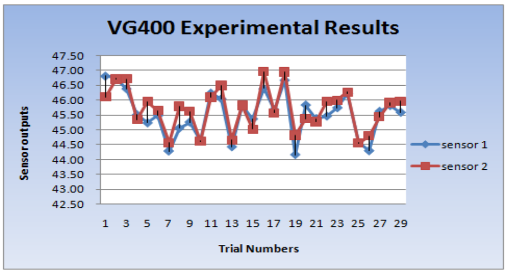

Figure 20. VG400 experimental results (Soil Moisture)

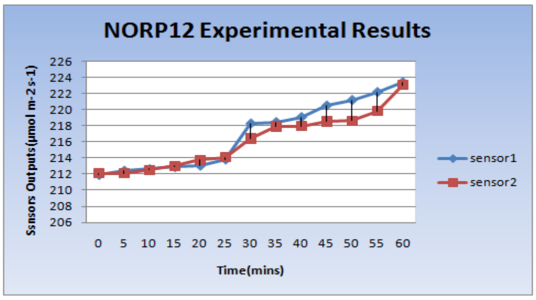

Figure 21. NORP12 experimental results (Light Intensity)

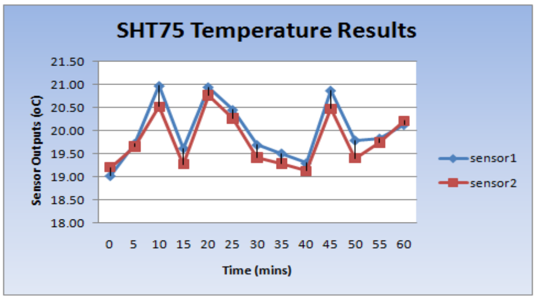

Figure 22. SHT75 experimental results (Ambient Temperature)

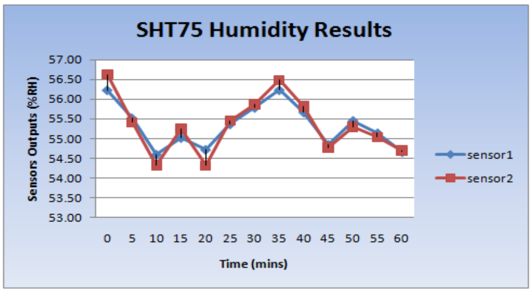

Figure 23. SHT75 experimental results (Relative Humidity)

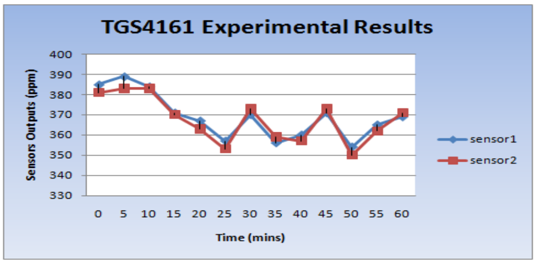

Figure 24. TGS4161 experimental results ($C0_2$)

The results obtained from the experiments show small variations between the readings of the two sensors. Future experiments will entail comparing data collected from these sensors with pre-calibrated standard devices to obtain more accurate results.

VI. Conclusions and Recommendations

The research team is involved in developing a fully automated greenhouse climate monitoring and control system for optimal growth of plants. Several sensors have been proposed to be utilised. This paper reviews some of these sensors and addresses the advantages and disadvantages of using them. Five sensors were found to be most suited for the prototype being developed namely, SHT75, TGS4161, THERM200, VG400 and NORP12. Experiments were carried out to test the accuracy of each sensor. From the experimental results, it was possible to infer that these sensors are accurate and reliable. However, in our future work, it is recommended to compare data collected from these sensors with pre-calibrated standard measurement instruments to obtain more accurate results.

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