Real-Time Monitoring of Modular Carbon Capture Machines with Sensor Networks and Node-RED

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Abstract—**Carbon Capture (CC) technology captures carbon from the air for utilization or storage. Heavy industries utilize CC to reduce carbon emissions; however, there are no suitable CC solutions for micro, small, and medium industries (MSME). This paper investigates a real-time carbon dioxide (CO_2) monitoring framework for fishery smoking machines used by cottage industries. The proposed CO_2 monitoring system uses a wireless data transmission system with the XBee Pro module. Data is sent to Node-RED software for collection, monitoring, and analysis, providing stable data transmission. A controlled experiment was conducted to determine the CO_2 measuring reliability of the MG-811 CO_2 sensor, which is installed in the filter box of the small-scale modular CC (MCC) machine, by comparing its measured data to the CO_2 emissions measured manually with the Testo 440 CO_2 digital measuring probe. Data was collected every 15 minutes over a four-hour span. It was found that the CO_2 emissions measured using the proposed real-time setup were consistent with the values collected from the Testo 440 device. This demonstrates that the small-scale modular CC machine is a feasible and frugal engineering solution that can be used to sequester CO_2 emissions in cottage industry settings. Furthermore, the results imply that a real-time monitoring system employing low-cost materials with minimal technological complexity, featuring wireless data transfer with sufficient sensitivity, has the potential to be deployed in heavy industries on a wider scale.**

Keywords— Carbon capture, carbon emission monitoring system, XBee pro module, Node-RED, sensor networks

I. Carbon Capture Technology

Carbon dioxide (CO_2) plays a crucial role in absorbing radiation and trapping heat to maintain a conducive temperature for life on Earth. However, the continuous rise in CO_2 concentrations due to intensive human activities shows no sign of saturation in radiation absorption [1]. To regulate global temperatures and maintain them below 1.5°C, Carbon Capture (CC) technology has emerged as a viable solution for mitigating climate change. CC reduces anthropogenic carbon emissions by capturing and sequestering excess greenhouse gases (GHG), primarily CO_2, for utilization and/or storage [2]. Globally, CC is extensively used by heavy industries such as cement production and oil refining. However, carbon emissions are not exclusively attributed to heavy industries. Shabir [3] reported that GHG emissions from the food processing industry could increase global carbon emissions by 30% by 2050. Moreover, studies on the food industry in Malaysia have shown consistent growth [4]. Recently, scaled-down CC systems have been implemented in buildings to reduce carbon emissions through micro-combined heat and power cogeneration [5]. This has inspired the development of small-scale and modular CC machines for food processing by micro, small, and medium enterprises (MSME). Therefore, to ensure that the operational sustainability of the CC technology is practical for MSME level, it is imperative to bridge the digital and techno-economic gaps by employing low-cost CO_2 emission monitoring framework that requires minimal technological complexity.

Although there are many facets of monitoring carbon emissions i.e., CO_2, temperature, humidity etc., this paper exclusively discusses on the real-time CO_2 emission monitoring. For this purpose, MG-811 sensor module which is highly sensitive to CO_2, was selected. When CO_2 particles attach to the electrode, the resistance increases, resulting in a smaller current through the sensor circuit and a lower output voltage reading [6]. The typical output voltage for the MG-811 ranges from 100 to 600 mV, corresponding to 400-10,000 parts per million (ppm) CO_2, which is approximately 0.775-19.374 kg CO_2/L. Hence, the MG-811 may be suitable for monitoring CO_2 emissions from fish smoking machines used in the production of smoked fish by cottage industries [7]-[8]. The MG-811 sensor module is compatible with Arduino, compatible for integration of wireless sensor networks.

Wireless sensor networks are widely utilized by industries for monitoring energy and environmental quality control [9]-[10]. The XBee Pro Module, a low-cost mesh communication protocol adhering to the IEEE 802.15.4 ZigBee standard, is suitable for MSMEs. It requires low power, has a transmission range of less than 100 m, is compatible with microcontrollers, and operates on a license- free spectrum. It has a data rate of 250 kbits/s with a low error rate as a communication link [9].

To complement the sensor network, the open-source web-based flow editor – Node-RED, is used as an analyzer and monitoring unit for receiving, processing, analyzing, and displaying real-time data. With an internet connection, the Node-RED dashboard can be monitored remotely from any terminal, including smartphones [10]. Furthermore, Node-RED functions as a data logger, enabling users to obtain a copy of the real-time data by generating a CSV file.

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II. CARBON CAPTURE TECHNOLOGY

A. Modular Carbon Capture Machine Design

In this work, the modular carbon capture machine (MCC) is designed to capture exhaust discharge from a fish smoking machine. The smoking machine used in this experiment is the Smoking Automation with Hybrid Heating Source (SMOKAHS). It is an insulated fish smoking machine with dual heating sources using liquefied petroleum gas (LPG) and mangrove firewood [8]. The scope of this study does not extend to carbon storage, as the focal objective is to determine the reliability of a cost-effective CO_2 monitoring framework. The MCC comprises four main systems, as shown in Figure 1. First, the direct air capture system which consists of (a) exhaust pipe from the SMOKAHS and (b) the aluminum duct – similar to a local exhaust ventilation duct system. This system captures the CO_2 by sucking smoke into the duct which is directly connected to the smoking machine's outlet. The high-temperature captured smoke is then cooled by (c), the cooling unit system, which utilizes Peltier-based thermoelectric technology for its portability due to the absence of refrigerants. After cooling, the captured smoke is mechanically filtered using a HEPA filter installed in (d), the filtering system, before discharged into the water tank smoke storage unit through (e), the air exhaust system.

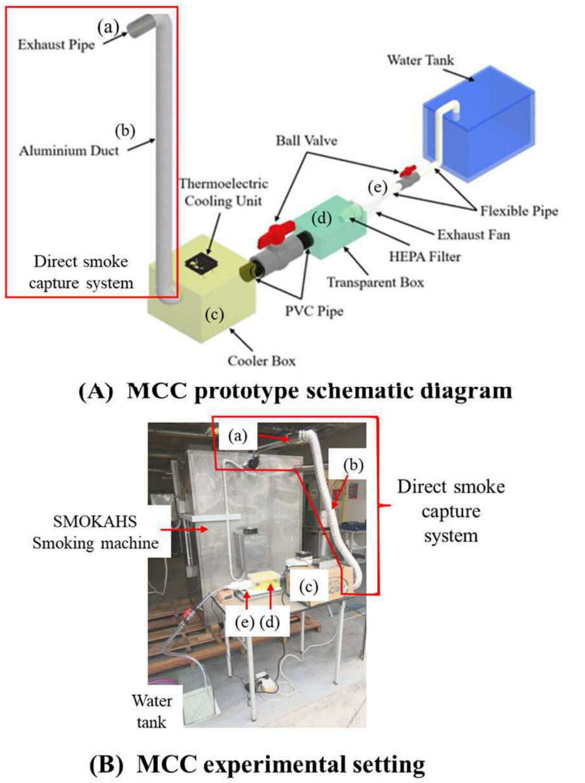

Figure 1. Modular direct air carbon capture (MCC) prototype. (a) and (b) are the direct air capture system. (c) is the cooling unit system. (d) is the filtration system and the CO2 sensor is in the filter box. (e) is the exhaust system.

B. Measuring carbon dioxide emission

The concentrations of CO_2 captured by the MCC were measured manually using the Testo 440 CO_2 probe and digitally via the MG-811 CO_2 sensor. The MG-811 is connected to an Arduino UNO microcontroller. CO_2 readings were collected at 15-minute intervals over four hours span, which is the average duration required for the SMOKAHS to complete a smoking cycle [7]. CO_2 concentration was measured manually from the water tank using Testo 440 CO_2 probe. Given that the water tank is not sealed airtight, the concentration of CO_2 around the water tank area was also measured with the Testo 440 CO_2 probe as a countermeasure for potential leakage. Meanwhile, the digital data were collected in the airtight sealed filter box (figure 1(d)) which housed the MG-811 sensor. The collected data were compared to evaluate the feasibility of employing an affordable and accessible sensor network architecture comprising the XBee Pro Module and the open-source Node-RED platform for CO_2 emission monitoring framework.

C. Carbon dioxide emission monitoring system

The proposed CO_2 emission monitoring framework for system networks utilizes a wireless data transmission system incorporating the XBee Pro module, as illustrated in Figure 2. The operation of the CO_2 monitoring framework system is detailed in the flow chart shown in Figure 3.

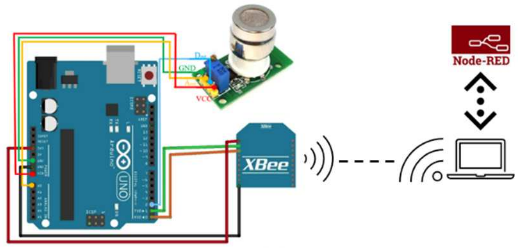

Figure 2. CO_2 sensor network diagram. On the left is the circuit diagram for the MG-811 and XBee connection to Arduino UNO. The transmitted data is received by XBee Pro Module connected to the data inquisition terminal (laptop). The received data is analyzed by Node-RED and the real-time kg CO_2 emission is displayed for monitoring.

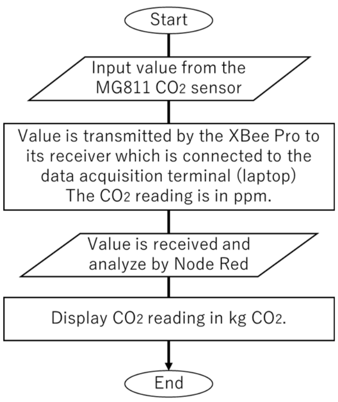

Figure 3. CO_2 emission monitoring system operation flow chart.

CO_2 concentration is measured using an MG-811 CO_2 sensor connected to an Arduino UNO microcontroller with XBee connectivity. The Arduino board substitutes the explorer board to wirelessly communicate the CO_2 concentrations in real-time via the XBee Pro transmitter to its receiver, which is connected to the data acquisition terminal, in this case, a laptop. The received data is retrieved and analyzed by Node-RED. Within Node-RED, the CO_2 concentration in ppm is converted into kg CO_2 readings based on equations (1) and (2). Equation (3) details the calculation for CO_2 measurement by the Testo 440. Here, V_m is standard molar volume of ideal gas (at 1 bar and 273.15 K), M_{CO2} is the molecular weight of CO_2 gas and V_C is the volume of container.

$$CO_2\ ppm = \frac{V_m}{M_{CO_2}} = \frac{22.71108\ L/mol}{44.01\ g/mol} \quad (1)$$

Therefore, for the filtration box where the MG-811 CO_2 sensor is located, the CO_2 value in kilograms, kg CO_2 is:

$$kg\ CO_2 = \frac{M_{CO_2}}{V_m} \times V_C = 1.9378\ g/L \times 1.2L/1000 \quad (2)$$

And for the water tank where the Testo 440 CO_2 probe reading is taken, the kg CO_2 value is:

$$kg\ CO_2 = \frac{M_{CO_2}}{V_m} \times V_C = 1.9378\ g/L \times 12L/1000 \quad (3)$$

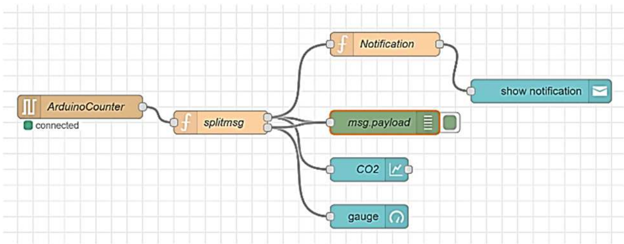

Figure 4. Configuration of nodes set up in Node RED.

Figure 4 illustrates the configuration of nodes in Node-RED used to analyze and visualize CO_2 emissions data, specifically following the relationships defined by equations (1) to (2). The setup begins with the ArduinoCounter node, which continuously collects CO_2 concentration data from the MG-811 sensor that is connected to an Arduino device. The status indicator showing "connected" confirms that the node is actively receiving data. This data is then passed to the splitmsg function node, which splits the incoming message payload into manageable parts for subsequent processing.

For data visualization, the CO_2 Chart node updates the trend chart on the dashboard, displaying CO_2 levels over time and enabling the identification of trends and fluctuations. The Gauge node provides a real-time display of the current CO_2 concentration, updating the "PPM Value" gauge on the dashboard for immediate user assessment.

Finally, the Notification function node evaluates these data segments against predefined thresholds to determine if any alerts should be triggered. If the CO_2 levels exceed safe limits, this node generates a notification message. Simultaneously, the msg.payload node organizes the data for use in various dashboard components, ensuring it is correctly formatted for visualization. Then, the Show Notification node triggers visual alerts if CO_2 concentrations surpass safe thresholds, ensuring that users are promptly informed of any critical conditions. This comprehensive node configuration in Node-RED ensures efficient real-time data collection, processing, visualization, and alerting, thus supporting effective monitoring and management of CO_2 emissions in the modular carbon capture machine.

III. Results and Discussion

A. *Reliability of MG-811 CO_2 compared to Testo 440 CO_2*

Figure 5 illustrates the CO_2 concentrations collected at 15-minute intervals. The blue circle marker represents the Testo 440 CO_2 manual measurements, the orange square marker denotes digital measurements from the MG-811 CO_2 sensor, and the green triangle marker shows CO_2 concentrations in the surrounding area by Testo 440. The dotted line shows the temperature fluctuations in the cooling box (figure 1(c)) taken by an inbuilt thermocouple in Celsius degrees (°C).

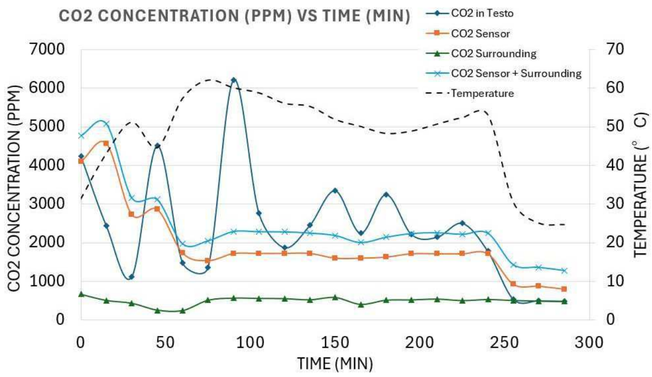

Figure 5. CO_2 Concentration VS Time.

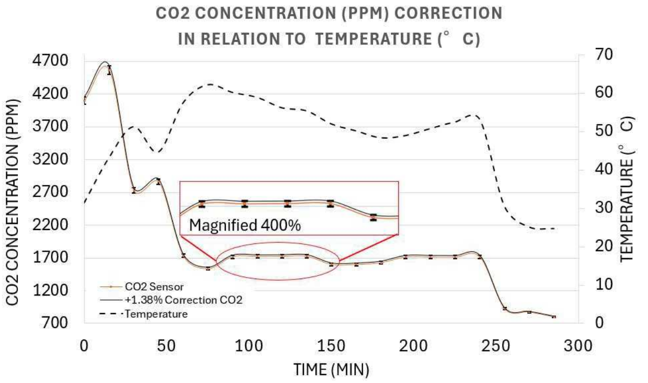

Figure 6. CO_2 Concentration Correction in Relation to Temperature.

Figure 5 illustrates the CO_2 concentrations collected at 15-minute intervals. The blue circle marker represents the Testo 440 CO_2 manual measurements, the orange square marker denotes digital measurements from the MG-811 CO_2 sensor, and the green triangle marker shows CO_2 concentrations in the surrounding area by Testo 440. The dotted line shows the temperature fluctuations in the cooling box (figure 1(c)) taken by an inbuilt thermocouple in Celsius degrees (°C).

The measurement data obtained with the Testo 440 CO_2 probe exhibit instability, however, the decline in CO_2 concentration is observed. This was due to the decrease of firewood and the smoking process progressed. Intermittent firewood mass check at minute-150 confirmed the reduction of firewood mass from 508g to 323g. The digital measurements by MG-811 also corresponded with the declining trend. However, the values of the collected data were about 500 ppm lower compared to the manually collected data points.

To investigate this discrepancy, the CO_2 concentration measurements collected from the surrounding area were analyzed. The plotted data curve was found to be comparable with the sensor's data. Furthermore, the average range was approximately 500 ppm to 600 ppm. These values matched with the value differences between the manually and digitally collected data. This confirmed the CO_2 leakage into the not airtight water tank, where the manual measurements were taken. Therefore, the CO_2 concentrations measured by the MG-811 CO_2 sensor were adjusted by adding the CO_2 concentrations from the surrounding area as shown in equation (4). The adjusted data is denoted as CO_{2x} and compared with the data collected from the water tank measured by Testo 440 CO_2 probe.

$$CO_{2MG811} + CO_{2Surrounding} = CO_{2x} \quad (4)$$

The adjusted MG-811 CO_2 reading, depicted by the light blue marker 'x', correlates with the measurements taken from the water tank by Testo 440 CO_2.

According to Glovisol [11], air temperature has slight implication on the MG-811 readings. For temperature ranging from 45℃ < x < 50℃ is +1.45% < x < +1.82%. Hence, the average correction taken from the experiment data pool is +1.38%. The error margin deviation shown at 400% magnification in figure 6 is insignificant. This suggested that the affordable MG-811 CO_2 sensor is reliable as CO_2 emission sensor for cottage industry and/or domestic use scale MCC machine.

B. *Data collection in Node Red*

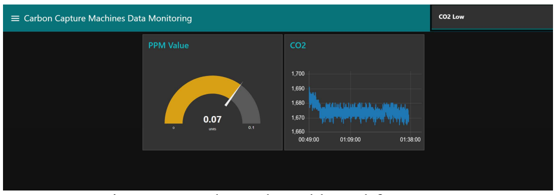

Figure 7. Node-Red Dashboard for CCM.

Figure 7 displays the Node-RED dashboard for real-time monitoring of CO_2 emissions using the MG-811 sensor. The dashboard is divided into several key components designed to offer a clear view of CO_2 data for the MCC machine. The Real-Time Data Display featured a PPM Value Gauge on the left side of the dashboard. This gauge shows the current CO2 concentration as measured by the MG-811 sensor, with a needle indicating the current measurement, which read 0.07 ppm in that instance. This real-time display allows users to quickly assess the CO_2 levels. Adjacent to the gauge is the CO_2 trend chart. It shows the CO_2 concentration levels over time. The x-axis represents the time span, while the y-axis indicates the CO_2 concentration in ppm. The chart is updated every second, displaying data collected helping in identifying trends and fluctuations in CO_2 levels for better analysis.

For historical data analysis, the dashboard includes a data log table listing timestamped records of CO_2 concentrations, and a statistical analysis section that shows the average, minimum, and maximum CO_2 levels over the monitoring period. The alert system includes threshold alerts that provide visual notifications if CO_2 levels exceed predefined safe limits, and a notification log that records all alerts and notifications sent during the monitoring period.

IV. Conclusion

The prototype of the MCC machine successfully captured CO_2 emissions from the exhaust of the fish smoking machine and directed the smoke through a vent system into the cooling and filtering systems, eventually storing it in a water tank unit. This functionality was validated through measurements taken by both the MG-811 CO_2 sensor located in the filter box and the Testo 440 CO_2 probe taken in the water tank and its surroundings. The data from the MG-811 was successfully transmitted to the XBee Pro Module, and the real-time data were displayed on the Node-RED web-based dashboard. It was found that the collected CO_2 concentration in the water tank storage unit corresponded with the data measured by the MG-811 CO_2 sensor after adding the readings from the surrounding area. This revealed air leakage into the water tank storage unit. An MCC design amendment is required to ensure the storage unit is airtight. The MG-811 sensor is slightly temperature-sensitive with an error averaging +1.38%. It is important to note that the MG-811 is a solid electrolyte, and the sensitivity may age and dull as CO_2 particles build up. Therefore, the NDIR infrared CO_2 sensor should be explored in future research. Overall, the wireless transmission of real-time concentrations of CO_2 emissions measured by the MG-811 CO_2 sensor via the XBee Pro Module to Node-RED for CO_2 emission monitoring proved to be seamless and reliable. This controlled experiment confirmed the feasibility of the MCC machine for cottage industries and underscored the reliability of low-cost sensor networks and Node-RED for small-scale CO_2 emission monitoring.

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