Integration of Gas Sensors as an Exhaust Gas Monitoring Device from Green Roasting Process of Various Coffee Beans

Samsidar¹, K N Sawitri¹, R Purbakawaca¹, M Ridho¹, Heriyanti², L Marlinda² and Sutrisno²*

¹Department of Physics, ²Department of Chemistry, Faculty of Science and Technology, Universitas Jambi

*E-mail: herasutrisno@unja.ac.id

Abstract. The exhaust gas monitoring system in the coffee roasting process continues to be developed considering the need for more complex roasting coffee beans information. The integrated gas sensor is designed by utilizing a microcontroller controller to see the exhaust gas during the roasting process. The exhaust gas produced during the roasting process is monitored by integrating sensors device to measure exhaust gases (CO, CO₂, NOₓ and SO₂). Furthermore, measurements were made by monitoring exhaust gas during roasting of Arabica, Liberica and Robusta coffee beans from Jambi province. The results showed that the total CO concentration in Liberica coffee was 2,121 ppm, Robusta 1,930 ppm and Liberica 1,535 ppm while for CO₂ was Liberica 21.3 ppm; Robusta is 22.2 ppm; Arabica is 22.4 ppm, and for NOₓ is Liberica 303 ppm; Robusta 304 ppm; Arabica is 287 ppm, and the SO₂ content for all types of coffee is 0 ppm. The highest exhaust gas concentration occurs after roasting lasts > 20 minutes and at a temperature of 210 - 230°C. It concluded that the integrated gas sensor can be used for the measurement of exhaust gas in the process of coffee beans roasting with the results of measurement of CO exhaust concentration in Liberica coffee is higher than Robusta and Arabica coffee beans.

1. Introduction
Roasting is the processing of coffee which is accompanied by physical and chemical changes, namely changes in temperature, humidity, and release of exhaust gases. Monitoring of exhaust gas is important for considering the level of pollutants produced from the roasting process and it will have an impact on the polluted environment. The exhaust gas from the roasting process is namely, particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NOₓ), etc. The relationship between the quantities of pollutants released into the atmosphere associated with the roasting process is stated by the emission factor. The emission factor in the roasting process is calculated by dividing the weight of pollutants on the weight of the roasted coffee beans [1]. The average emission factors for continuous roaster are PM 0.289 Kg/ton, VOC 0.702 Kg/ton, CO 0.8 Kg/ton, CO₂ 60.6 Kg/ton, and NOₓ 0.05 Kg/ton. While for batch roaster are PM 2.1 Kg/ton, VOC 0.43 Kg/ton, CO₂ 90.3 Kg/ton, and NOₓ 0.05 Kg/ton [1–3].
The monitoring will be more effective if the exhaust gas released process is associated with temperature and time parameters. If the exhaust gas can be monitored by linking these parameters, the roasting process can easily be controlled to create exhaust gases that are standard and environmentally friendly. The fundamental problem in the process of roasting coffee beans is the accuracy of time (t) and temperature (T) selection as a thermal process that matches the characteristics of the coffee beans. Temperature and roasting time greatly affect the chemical and physical changes that occur during roasting. In general, chemical changes that occur are changes in chemical composition, namely, an increase in the content of glucose and free fatty acids, a decrease or increase in caffeine content, a decrease in protein content, and unsaponified compounds. It is well known that the roasting process causes the chemical and physicochemical characteristics of green coffee beans. The coffee beans will experience changes such as colour, pH level, taste and aroma associated with the Millard reaction [4,5]. Thermal reaction in the roasted coffee beans is decarboxylation, dehydration, fractionation, isomerisation, polymerization, and sugar complexes [6,7].

The evaporation process occurs at a temperature of 160-190°C, after which coffee undergoes a series of chemical reactions that will give flavour and aroma at the end of roasting which is around 200-250°C. During the chemical process, coffee releases organic compounds, carbon dioxide, and other gases which are measured as exhaust gases [8]. Exhaust gases that come out from roasting drums are particulate matter (PM), Nitrogen (N2), Carbon dioxide (CO2), steam, Oxygen (O2) and a mixture of 700 other volatile compounds (VOCs) such as ketones, aldehydes, pyrroles, furans, pyridine, and a sulphur compound. In addition, colour changes have also been monitored during the roasting process [9]. At 0-20 seconds there is no colour change. A slight dark colour change will be obtained in a period of 20-60 seconds. Then at 60-100 seconds with a roasting temperature above 160°C, the coffee will be lighter which means that the ripening process occurs. Therefore, temperature and time are important factors when roasting which show how the relationship between temperature, time and level of coffee brightness.

During the roasting process, a chemical composition changes and is monitored qualitatively. The determination of the chemical composition contained in the exhaust gas is measured by chromatography. The determination of the chemical composition is intended as the right temperature control that will be set during the roasting process to obtain maximum roasting results. The process of roasting reaches a maximum after 9 minutes which is indicated by the amount of exhaust gas measured [10]. Monitoring and controlling process is a standardization process in the roasting process. The decrease in mass, density, humidity, colour and taste are standard variables measured in the coffee processing industry. However, to determine the standardization by considering these characteristics is considered quite complicated, expensive and time-consuming because it must require sample preparation and even chemical manipulation. Therefore, this monitoring is determined offline in the laboratory. For this reason, on-line monitoring and evaluation techniques have been carried out. based on the results of monitoring, significant water content loss occurs after a period of 3-4 minutes and at the end of the roasting process the density of coffee is obtained around 50% -60% [11], this monitoring shows the relationship between moisture content and seed density with time.

In this study, we focused on some exhaust gases measuring sensors in a roasting device integrated with a temperature sensor are combined, the change in time will be the sensor parameters. The sensor processing begins with the design, assembly, programming which will then be validated against each exhaust gas sensor (CO, CO2, NO, NO2, SO2). After validation, the exhaust gas sensor will be integrated using a microcontroller against temperature sensors with time variables. The data collection will be carried out on the exhaust gas generated from the roasting process of Liberica, Arabica and Robusta coffee beans originating from Jambi province. Furthermore, data analysis is carried out in the form of exhaust gas produced for each type of coffee beans. We have recently described the thermal behaviour and characterization of roasted Liberica, Arabica, and Robusta coffee beans using DSC, spectroscopic methods and XRD. The DSC analysis shows that the three type of coffee has a similar characteristic of thermal properties. The spectroscopic analysis has done using by FTIR and LC/MS, the result describes that the roasted coffees consist of...
nitrogen compounds such as choline, trigonelline, and caffeine; chlorogenic acids, and sucrose groups. The XRD analysis shows that there is a formation of polysaccharide crystal, but the structure is not confirmed yet [12].

The purpose of this study is to integrate with environmentally friendly exhaust gas monitoring sensor that is monitored on-line, studying the effect of time, temperature changes and water content on the exhaust gas produced during the roasting process of several types of coffee beans. This information as the basis for determining the quality of coffee by connecting the physical and chemical processes that occur during the roasting process. In Nebath's 2014 study, MG-811 was used for CO₂ measuring devices to make time efficient in measuring harmful gases [13]. In the 2015 Fuertes research, MG-811 was used to monitor air pollution integrated with IoT (Internet of Thing), in order to monitor air pollution in real time. In Reilly's 2015 study, MQ-131 was used on wireless air quality measurements at a relatively low cost. Sensor MQ-136 can be used to Implement Air Pollution Monitoring Systems Based on Air Pollution Standards Index [14].

2. Materials and methods

2.1. Materials
In this experiment, the Green coffees used were obtained from Jambi Province, Indonesia. Liberica coffee from Tanjung Jabung Barat District, Arabica coffee from Kerinci District, and Robusta from Merangin [12].

2.2. Methods
The preparation of roasting followed the procedure reported in the previous article [12]. The system design consists of hardware system design, software system design, and the collection process.

2.2.1. Hardware System Design
Hardware design is based on the principle of voltage changes when there is a change in temperature and concentration of exhaust gas, namely carbon monoxide (CO), carbon dioxide (CO₂), Sulphur dioxide (SO₂) and nitrogen oxides (NOₓ). The main hardware circuit consists of a series of regulators, Arduino Mega 2560 system circuit, LCD circuit, RTC circuit, the gas sensor circuit and thermocouple circuit, as presented in Figure 1.

![Figure 1. Hardware circuit scheme](image)

This circuit uses LM7805 controllers and two 100 μF capacitors. The LM7805 has an internal feature to limit current and non-active features if the temperature exceeds the threshold so that the LM7805 is immune to overload. The measurement data will be displayed using a TFT LCD based on capacitive sensors so that users can touch and press the menus on the display. This LCD size is 10.5 inches, has an SD logger slot for storing data. The LCD pin is connected to Arduino Mega 2560. The signal sent by Arduino is controlled on the LCD using the SSD1963 controller.
Temperature reading during the roasting process is automatically carried out using a K-type thermocouple glass insulation. The design of insulating glass in a thermocouple causes the thermocouple to work at high temperatures up to 500°C so that it matches the roasting temperature profile of the coffee. Thermocouples will work more optimally when coupled with an amplifier. This research uses the MAX31850 amplifier. The working principle of the MAX31850 thermocouple is to use cold-junction compensation, where the thermocouple serves to capture the temperature difference between the two ends of the thermocouple cable. Based on the MAX31850 datasheet, the amplifier digitizes analogue signals from type K thermocouples to data with a 14-bit resolution with a 1-wire interface.

Real Time Clock (RTC) is added to the hardware system to record the time and date when measuring. The RTC used is the DS1307 RTC, where the data is valid until 2100. Time is recorded in the HH: MM: SS format, while the date is recorded in the YYYY/MM/DD format. The RTC module is connected to Arduino Mega2560 via serial cable 2 communication. The current consumed by the module during running is small from 5000nA with a working temperature of -40 to 80°C. Data taken from the RTC module uses a 24-hour data format. Measurement data will be taken every 1 second for +30 minutes for one time roasting coffee. Each data will be stored in a 16 GB SD card in text format so that further analysis can be done using the MS application, EXCEL.

There are four gas sensors that will be installed in the exhaust gas monitoring tool that is integrated with the coffee roasting process, namely MQ136, MQ9, MG811 and MQ131. Each sensor was chosen because of its sensitive properties to certain gases, namely MQ136 to SO2, MQ9 gas to CO gas, MG811 to CO2, and MQ131 to NOx. The four gas sensors are arranged in parallel and each sensor is connected in series with the resistor R_L. The source voltage required in the operation of the sensor is 5V. The sensor will read the concentration of gas in the form of ADC. The conversion process of units to ppm will be carried out at the calibration stage. Figure 2 shows the hardware system used.

2.2.2. Software System Design
Software design is a program making process based on tool work algorithms as presented in Figure 3. The design includes the preparation of the Arduino Mega2560 program using the Arduino IDE 1.6.12 application for computing purposes. Equation 2 in the calibration process is entered into Arduino Mega2560. The temperature value of the thermocouple and the gas concentration value of the four sensors are then displayed on the TFT LCD in graphical form and stored on the SD card in text form. All data is added with time information from the RTC output. If an error occurs in the circuit or data, an error message will be displayed on the LCD. Before operating the monitoring tool, users are required to fill in the usage data of the device such as username, place of measurement, type of coffee and weight of coffee. If the user deactivates the monitoring tool, the data will remain automatically saved.
2.2.3. Collection Process

Exhaust gas measurements are carried out during the roasting process of Liberica, Arabica, and Robusta coffees that originating from Jambi Province. Exhaust gas is monitored in real time from the start until the roasting process ends. Furthermore, the appearance of the reading results will be displayed in the form of graphs which interpret the magnitude of the concentration of the exhaust gas to time and temperature. Figure 4 shows the exhaust gas measurement process.
3. Results and Discussion

3.1. Exhaust Gas on Liberica Coffee

The exhaust gas produced in the Liberica coffee roasting process depends on the length of time needed during the process. Furthermore, the roasting temperature affects the magnitude of the output gas concentration. The effect of the output gas on time and temperature can be seen in Figure 5 and 6.

![Figure 5. Effect of time on the exhaust gas in the process of roasting Liberica coffee](image)

![Figure 6. Effect of temperature on the exhaust gas in the process of roasting Liberica coffee](image)
From Figure 5 and 6, the concentration of CO$_2$ gas tends to be constant at 0.7 - 1.5 ppm. The highest concentration when measuring 23 minutes with a temperature of 225°C with a concentration of 1.5 ppm. While the NO$_x$ gas concentration has a relatively higher concentration compared to CO$_2$ gas which is around 10-23 ppm and the highest concentration changes also occur at 23 minutes with a temperature of 225°C, where the NO$_x$ concentration before experiencing an increase was 16 ppm at 220°C. The CO gas concentration is much higher than the other gas concentrations in the range of 50-254 ppm. The maximum increase occurred at the time of measurement in the 22nd minute and the temperature of 220°C was 254 ppm. The increase in CO gas concentration is not constant with increasing time and temperature because at 6 minutes (temperature 150°C), 7 (160°C), 8 (165°C), and 9 (170°C) the concentration increases from 64 ppm to 88 ppm (minutes 5th with a temperature of 145°C). The next, at 7 minutes (160°C) = 115ppm, minute 8 (165°C) = 140 ppm, minute 9 (170°C) = 135 ppm and decreased at 10 minutes (185°C) which is 70 ppm and began to experience increase in concentration at minute 20 (210°C) = 115 ppm. The total exhaust gas of CO$_2$ in the roasting of Liberica coffee beans is 21.3 ppm; NO$_x$ gas 303 ppm and SO$_2$ 0 ppm.

### 3.2. Exhaust Gas of Robusta Coffee

The exhaust gas concentration in the Robusta coffee roasting process can be seen as in Figure 7 and 8.

![Figure 7](image_url)

**Figure 7.** Effect of time on the exhaust gas in the Robusta coffee during the roasting process

![Figure 8](image_url)

**Figure 8.** Effect of temperature on the exhaust gas in the Robusta coffee during the roasting process

The CO$_2$ concentration in the range of 0.8 - 1.7 ppm, the highest increase in concentration is at 23 minutes with a temperature of 225°C which is 1.7 ppm. Furthermore, NO$_x$ concentrations ranged between 10-21 ppm and changes in concentration increase occurred at the 21st with a temperature of 220°C which was 16 ppm and at 22 minutes with a temperature of 225°C which was 21 ppm. The concentration of CO is very significant compared to the concentration of other exhaust gases, which is...
around 40 - 473 ppm. The change in concentration is not always linear with changes in time and temperature because at 4 minutes with a temperature of 150°C, CO concentration increases from 56 ppm to 86 ppm, and the peak increase in CO gas concentration occurs again in the 20th minute with a temperature of 210°C and continues to increase until the 22nd and 23rd minutes at 225°C which is around 473 ppm. The total exhaust of CO₂ in the roasting of Robusta coffee is 22.2 ppm; NOₓ gas is 304 ppm and SO₂ is 0 ppm.

3.3. Exhaust gas on Arabica Coffee
The concentration of exhaust gas in Arabica coffee is as shown in Figure 9 and 10.

From Figure 9 and 10, it can be seen that the concentration of the exhaust gas tends to have a tendency to change the time and temperature during the roasting process. CO₂ concentration in the range of 0.7-1.8 ppm and an increase occurs at 22 minutes with a temperature of 225°C which is 1.3 ppm and at 23 minutes with a temperature of 230°C is 1.8 ppm. Then for NOₓ gas, the concentration range is 8 - 27 ppm and a significant increase also occurs in the 22nd minute with a temperature of 230°C by 18 ppm and at 23 minutes with a temperature of 230°C by 27 ppm. Whereas for CO it ranges from 16 - 356 ppm. The highest exhaust gas began to occur at minute 20 with a temperature of 215°C which was around 114 ppm and continued to increase until the 23rd minute at 230°C with 356 ppm. The total CO₂ exhaust gas in the roasting of Arabica coffee is 22.4 ppm; NOₓ gas is 287 ppm and SO₂ is 0 ppm.
3.4. Carbon monoxide (CO) concentrations in Liberica, Robusta and Arabica coffee
From the results of exhaust gas measurements of the types of coffee Liberica, Robusta and Arabica during roasting process obtained the most dominant concentration is CO gas which can be seen in Figure 11.

![Figure 11. CO concentration on roasting coffee of Liberica, Robusta and Arabica](image)

From Figure 11 it can be seen that Liberica coffee during the roasting process contributes the largest CO gas producer compared to Robusta and Arabica coffee, with total CO gas during the roasting process as much as 2.121ppm, followed by Robusta and Arabica coffee which is 1.930 and 1.535ppm, respectively. Likewise, when viewed from the temperature during the roasting process, it can be seen that Liberica coffee contains more CO exhaust compared to Robusta and Arabica coffee as shown in Figure 12.

![Figure 12. CO concentration on roasting coffee of Liberica, Robusta and Arabica](image)
From Figure 12 it can be seen that roasting temperatures can affect CO formation in Liberica, Robusta and Arabica coffee. The increase in CO occurred during roasting processes above 210°C to the final roasting temperature of 230°C.

For the three types of coffee, the highest concentration of exhaust gas is CO, followed by NOx and CO2. Heat from the roasting process causes some of the compounds contained in coffee to evaporate, oxidize, or break down into by-products, for example, CO, NOx and SOx [15]. The exhaust gas from the roasting process comes from the breakdown of sugar and oil contained in green coffee. PM is mainly derived from the outer shell of coffee which is released during roasting. In addition, NOx and CO can also come from the incomplete combustion of roaster fuel [3]. The higher roasting temperature, the more these gases are produced. CO2 is derived from caramelized reaction during roasting, which is an excess of oxidized sugar [12].

4. Conclusion

The monitoring of exhaust gas has been carried out in the process of roasting Liberica, Arabica and Robusta coffee by using an integrated exhaust gas monitoring system (time and temperature). The highest increase in the average exhaust gas output occurs during the roasting process which takes after 20 minutes with temperatures of > 215°C. The highest exhaust gas concentration occurred at Liberica coffee roasting at 2.121 ppm, followed by Robusta and Arabica coffee with concentrations of 1.930 ppm and 1.535 ppm, respectively.

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