Design and Implementation of a Low-Cost Gas Chromatograph System

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Abstract— **Gas chromatography (GC) is a vital analytical technique in space exploration and various scientific fields. This study presents the design and implementation of a low-cost gas chromatograph system suitable for educational purposes and basic research applications. The system utilizes air as a carrier gas, a silicon tube packed with silica gel as the column, and a TGS-813 gas sensor for detection. An Arduino Uno R3 microcontroller board manages data acquisition and processing, with real-time visualization achieved through MATLAB. The system successfully detected butane with a retention time of approximately 2 seconds, demonstrating its capability to separate and analyze volatile compounds. While the simplified components limit the system's sensitivity and resolution compared to commercial GC instruments, it effectively illustrates fundamental chromatographic principles. This low-cost approach makes GC technology more accessible for educational settings and could potentially contribute to the development of compact, affordable GC systems for future space missions, such as analyzing the chemical composition of Europa's icy surface**

Keywords— gas chromatography, low-cost, butane, Europa exploration, volatile organic compounds.

I. Introduction

Gas chromatography (GC) has been a cornerstone analytical technique in space exploration since the early days of planetary missions. Its ability to separate and identify volatile compounds makes it particularly valuable for astrobiology and planetary science. The method was first introduced by A.T. James and A.J.P. Martin in 1952, building upon earlier work in partition chromatography. This technique allows for the separation and analysis of complex mixtures of volatile compounds, making it invaluable in various fields such as petrochemical analysis, environmental monitoring, and food science [1].

Over the decades, GC has seen significant advancements in column technology, detection methods, and data handling techniques, greatly expanding its applications and improving its accuracy and sensitivity. The development of capillary columns, particularly fused-silica columns in the 1980s, marked a major milestone in GC technology, enabling high-resolution separations and broadening the technique's applicability across various analytical challenges [2].

In the context of space exploration, gas chromatography holds exceptional promise. Missions targeting environments like Europa's icy surface represent frontier applications where GC can provide unprecedented insights into chemical composition and potential biosignatures. The ability to perform in-situ analysis of volatile organic compounds could unlock critical understanding of extraterrestrial environments, potentially revealing indicators of past or present microbial life [3].

This research project emerges from the recognition that while advanced gas chromatography systems are powerful, there remains a significant need for accessible, low-cost alternatives that can democratize this analytical technique. By designing a budget-friendly gas chromatograph suitable for educational setting and basic research, this study aims to contribute to the broader goal of making sophisticated analytical techniques more widely available.

The primary objective of this project is to design and construct a gas chromatograph capable of separating, identifying, and quantifying volatile compounds—specifically butane—using cost-effective components and an innovative approach that demonstrates the fundamental principles of gas chromatographic analysis.

II. Literature Review

Gas chromatography has become a fundamental tool in various fields, including environmental monitoring, petrochemical analysis, and biochemical research, due to its ability to separate complex mixtures with high precision and sensitivity. The technique operates by injecting a sample into a carrier gas stream (typically helium or nitrogen), which passes through a column containing a stationary phase. Components in the sample are separated based on their interactions with the stationary phase and their volatility, with more volatile compounds eluting faster than less volatile ones [2].

In recent years, there has been significant interest in developing low-cost GC systems for educational and research purposes. Hinterberger et al developed an Arduino-based GC system for under \$100, making it accessible for teaching analytical chemistry [4]. Such systems often use alternative components to reduce cost while maintaining core functionality. In this project, a similar approach was taken by using a TGS 813 solid-state sensor as the detector instead of the more commonly used Flame Ionization Detector (FID). While the TGS 813 is cost-effective, it lacks the sensitivity and specificity of FID detectors, which could limit the system's ability to detect trace amounts of certain compounds. Additionally, instead of using a fused silica capillary column—standard in commercial GC systems—this project employed a silicon tube packed with silica gel. Although this setup is functional for basic separations, it may not provide the same resolution or efficiency as more advanced columns [5].

Another limitation of this project is the absence of an oven for temperature control. In commercial GC systems, an oven is used to regulate the temperature of the column, allowing for better separation of compounds with different volatilities. Without this feature, the separation efficiency may be compromised, particularly for complex mixtures [6]. Despite these limitations, this project demonstrates that a functional gas chromatograph can be constructed within a student budget using alternative materials and components.

III. Apparatus

The gas chromatograph for this project consists of a diaphragm pump, a silicon tube, a three-way valve, silica gel, a gas sensor, a breadboard, a micro controller, an LP gas sample, and some jumper wires. The complete setup can be seen in Fig. 1.

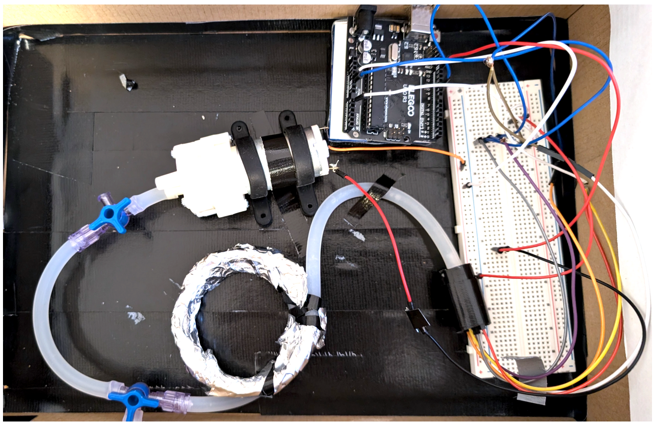

Fig. 1. Gas Chromatograph setup

A. Hardware Tools

1) *Diaphragm pump:* Air was chosen as the carrier gas for this experiment. Traditionally, inert gases such as helium, nitrogen or argon are used, but due to the low-cost nature of this project, a mini 6V diaphragm pump was selected to pump air into the column unit.

2) *Silicon Tube (Column):* A 1 m silicon tube was used as the column for this experiment, with inner and outer diameters of 5 mm and 8 mm, respectively. Crushed silica gel crystals were used to pack the column.

3) *Three way valve*: A three-way valve was installed to facilitate the mixing of the sample with the carrier gas before reaching the gas sensor. This valve serves as a critical junction point in the system, controlling the flow direction and enabling precise sample introduction.

4) *Gas Sensor (TGS - 813):* The TGS-813 gas sensor (solid state sensor) was selected for this project due to its specific capability that exhibits high sensitivity to propane and butane, making it ideal for analyzing LP gas samples. The sensor's quick response time and stable performance characteristics make it suitable for continuous monitoring in gas chromatography applications [7].

5) *Micro controller:* The Arduino Uno R3 serves as the primary microcontroller board for the gas chromatograph system. This board features 14 digital I/O pins (including 6 PWM outputs), 6 analog inputs, and operates with a 16 MHz ceramic resonator. Its built-in USB connection and power jack provide convenient connectivity options [8]

B. Software Tools

1) *Arduino IDE:* The Arduino Integrated Development Environment (IDE) is an open-source software platform designed for programming Arduino microcontrollers. It provides a user-friendly interface for writing, compiling, and uploading C++ code, enabling precise hardware control and simplifying microcontroller programming through comprehensive libraries [8].

2) *MATLAB:* MATLAB served as the primary data visualization and analysis tool, offering robust capabilities for real-time signal processing. The software facilitated dynamic data acquisition from the Arduino, parsing sensor readings and generating chromatographic plots through its powerful computational environment and serial communication capabilities [9].

IV. Methodology

A. Experimental Design and Procedure

The GC system utilizes air as the carrier gas, which is propelled through the GC column by a diaphragm pump. Traditionally, fused silica columns are employed in gas chromatography due to their inert nature and the ability to create a uniform stationary phase on their inner surface. These columns are valued for their porous structure and high surface area, which facilitate effective separation of analytes based on their interactions with the stationary phase.

In this implementation of a low-cost GC system, commercially available silica gel packets were used as an alternative to conventional GC columns. This substitution aims to reduce costs while still providing a suitable stationary phase for separation.

Liquefied Petroleum (LP) gas, primarily composed of butane, was chosen as the sample for analysis. Butane is an ideal candidate for this system due to several factors:

- It typically has a short retention time on most GC columns, making it useful for measuring gas hold-up time and assessing column efficiency.
- It is readily available in the market, ensuring easy access for experimentation and calibration.
- Its volatile nature makes it suitable for gas chromatographic analysis.

The butane sample was extracted using a syringe and introduced into the system through an injection unit. This unit consists of a three-way valve with one port connected to the carrier gas inflow from the pump, another to the packed silica column, and the third serving as the injection point. This configuration allows for the mixing of the butane sample with the carrier gas before it enters the column, ensuring proper sample introduction and separation. In theory, different substances in the sample interact differently with the column's stationary phase, depending on their chemistry. This causes them to travel through the column at different speeds, thus separating them [2].

Traditionally, the GC column is placed in an oven heats the sample and column to maintain a stable temperature environment, which is crucial for consistent and efficient separation of sample. For this system, the column is wrapped with aluminum foil to mimic this behavior in ambient temperature. The separated sample is then detected with a TGS- 813 gas sensor and analyzed through an Arduino unit. The data is then sent to MATLAB's built-in plotting functions for real-time display.

B. *Schematic and Data Workflow*

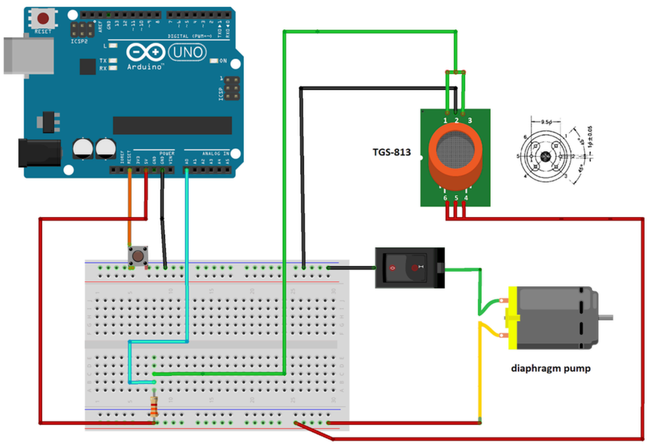

Fig. 2. GC System schematic

Fig. 2. illustrates the schematic diagram of the gas chromatography (GC) system. The components are connected to an Arduino board, which serves as the control and data acquisition unit. The system is set up as follows:

1) *Carrier Gas System:* The diaphragm pump, which provides the carrier gas flow, has its terminals connected to the 5V power supply and the ground (GND) of the Arduino board.

2) *TGS-813 Sensor Connections:*

- Pins 1 and 3 of the TGS-813 sensor, which are the output pins, are connected. This connection, known as V_c (circuit voltage), is then linked to the analog input A0 of the Arduino to log the detection of butane.
- The V_C connection is also connected to one end of a 10,000 Ω load resistor. The other end of this resistor is connected to the 5V supply of the Arduino.
- Pins 4, 5, and 6 of the sensors are connected to the 5V supply of the Arduino.
- Pin 2 of the sensor, also known as V_H (heater voltage), is connected to the ground of the Arduino board.

3) *Data Logging Control:* A reset button is incorporated into the circuit and connected to the Arduino board. This button allows the user to stop the data logging process after the sample has been detected and analyzed.

The data acquisition and analysis process involve real-time communication between the Arduino microcontroller and MATLAB software. The Arduino continuously samples the TGS-813 sensor's analog output at a rate of 100ms intervals, converting the readings to digital values. These values, along with corresponding timestamps, are transmitted through serial communication at 9600 baud rates to MATLAB.

MATLAB receives this data through a configured serial port connection and processes it in real-time. The incoming data stream is parsed into separate arrays for time, voltage, resistance, and calculates butane concentration. This processed data is then visualized through a dynamic plot, showing the chromatogram as it develops.

V. Results

The gas chromatograph system designed and implemented in this project demonstrated its capability to separate and analyze a butane sample within a low-cost framework. Upon injection of the butane sample into the system, a single peak was observed at approximately 5.4 seconds as shown in Fig. 3. This short retention time suggests that butane, being a relatively volatile compound, elutes quickly through the column. The use of a silicon tube packed with silica gel as the column material, rather than more advanced fused silica columns, likely contributed to the observed low retention time due to its basic separation efficiency.

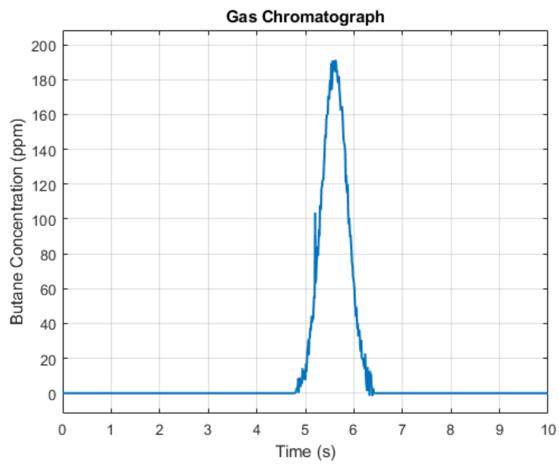

Fig. 3. Butane Concentration versus Time

The peak observed at 5.4 seconds in the chromatogram indicates the time at which the butane molecules, after interacting with the silica gel stationary phase, reached the TGS-813 sensor. The peak's shape and height could provide qualitative and quantitative information about the butane sample. However, the system's limitations, such as the absence of an oven for temperature control, might compromise the separation efficiency for more complex mixtures. Without precise temperature regulation, the interaction between the sample components and the stationary phase is less predictable, potentially broadening the peak or shifting its position. Despite these constraints, the system successfully showcases the basic functionality of gas chromatography in separating volatile compounds, offering a practical educational tool for understanding the technique's principles and potential applications in space exploration, particularly in analyzing the chemical composition of environments like Europa's icy surface.

VI. Conclusion

The low-cost gas chromatograph system successfully demonstrated the fundamental principles of gas chromatographic separation and detection of butane, achieving its primary objective within a student budget framework. The system effectively detected butane with a retention time of approximately 2 seconds, validating the basic functionality of the design. While the simplified components like the silicon tube packed with silica gel and the TGS-813 sensor provided adequate performance for basic separations, several improvements could enhance the system's capabilities. The addition of temperature control through a column oven would significantly improve separation efficiency and peak resolution. Upgrading to a more sophisticated detector and implementing automated sample injection would increase sensitivity and reproducibility. Furthermore, incorporating digital flow control and pressure regulation would enable more precise control over the carrier gas flow rate. Despite its limitations, this project successfully demonstrated that a functional gas chromatograph could be constructed using cost-effective alternatives while maintaining core analytical capabilities, making it a valuable tool for understanding chromatographic principles.

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Appendix

Arduino Code for the GC System

```
const int sensorPin = A0;
const float VC = 5.0;
const float RL = 10000.0;
const float R0 = 10000.0; // Sensor resistance in clean air (calibrate this value)

void setup() {
  Serial.begin(9600);
  Serial.println("Time,Voltage,Resistance,Butane_Concentration");
}

void loop() {
  float sensorVoltage = analogRead(sensorPin) * (VC / 1023.0);
  float sensorResistance = ((VC - sensorVoltage) / sensorVoltage) * RL;
  float ratio = sensorResistance / R0;

  // Butane concentration calculation (approximate, needs calibration)
  float butaneConcentration = 1000 * pow(ratio, -2.2);

  // Output data for serial plotter
  Serial.print(millis());
  Serial.print(",");
  Serial.print(sensorVoltage);
  Serial.print(",");
  Serial.print(sensorResistance);
  Serial.print(",");
  Serial.println(butaneConcentration);

  delay(100); // Adjust sampling rate as needed
}
```

MATLAB Code for Real-Time Monitoring

```
s = serialport("COM3", 9600); % Replace COM3 with your Arduino port
configureTerminator(s, "LF");

figure;
h = animatedline;
ax = gca;
ax.YGrid = 'on';
ax.YLim = [0 225]; % Adjust as needed


title("Gas Chromatograph");
ylabel("Butane Concentration (ppm)");
xlabel("Time (s)");

while true
    data = readline(s);
    values = str2double(split(data, ','));

    if length(values) == 4
        addpoints(h, values(1)/1000, values(4));
        drawnow
    end
end
```