

5.1: Dynamic Headspace Gas Chromatography Analysis

Gas chromatography (GC) is a very commonly used chromatography in analytic chemistry for separating and analyzing compounds that are gaseous or can be vaporized without decomposition. Because of its simplicity, sensitivity, and effectiveness in separating components of mixtures, gas chromatography is an important tools in chemistry. It is widely used for quantitative and qualitative analysis of mixtures, for the purification of compounds, and for the determination of such thermochemical constants as heats of solution and vaporization, vapor pressure, and activity coefficients. Compounds are separated due to differences in their partitioning coefficient between the stationary phase and the mobile gas phase in the column.

Physical Components of a GC System

A gas chromatograph (Figure 5.1.1) consists of a carrier gas system, a sampling system, a separation system, a detection system, and a data recording system.

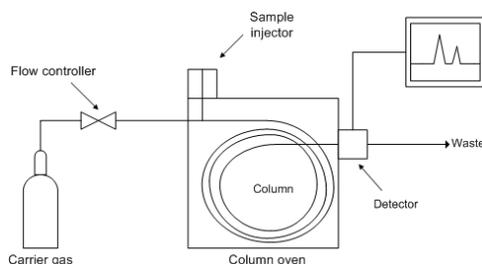


Figure 5.1.1 Physical components of a typical GC system. Adapted from http://en.Wikipedia.org/wiki/Gas_chromatography

An ideal separation is judged by resolution, efficiency, and symmetry of the desired peaks, as illustrated by

The carrier gas system consists of carrier gas sources, purification, and gas flow control. The carrier gas must be chemically inert. Commonly used gases include nitrogen, helium, argon, and carbon dioxide. The choice of carrier gas often depends upon the type of detector used. A molecular sieve is often contained in the carrier gas system to remove water and other impurities.

Auto Sampling System

An auto sampling system consists of auto sampler, and vaporization chamber. The sample to be analyzed is loaded at the injection port via a hypodermic syringe and it will be volatilized as the injection port is heated up. Typically samples of one micro liter or less are injected on the column. These volumes can be further reduced by using what is called a split injection system in which a controlled fraction of the injected sample is carried away by a gas stream before entering the column.

Separation System

The separation system consists of columns and temperature controlling oven. The column is where the components of the sample are separated, and is the crucial part of a GC system. The column is essentially a tube that contains different stationary phases have different partition coefficients with analytes, and determine the quality of separation. There are two general types of column: packed (Figure 5.1.2) and capillary also known as open tubular (Figure 5.1.3).

- Packed columns contain a finely divided, inert, solid support material coated with liquid stationary phase. Most packed columns are 1.5 – 10 m in length and have an internal diameter of 2 – 4 mm.
- Capillary columns have an internal diameter of a few tenths of a millimeter. They can be one of two types; wall-coated open tubular (WCOT) or support-coated open tubular (SCOT). Wall-coated columns consist of a capillary tube whose walls are coated with liquid stationary phase. In support-coated columns, the inner wall of the capillary is lined with a thin layer of support material such as diatomaceous earth, onto which the stationary phase has been adsorbed. SCOT columns are generally less efficient than WCOT columns. Both types of capillary column are more efficient than packed columns.



Figure 5.1.2 An example of a packed GC column.



Figure 5.1.3 An example of a capillary column.

Detectors

The purpose of a detector is to monitor the carrier gas as it emerges from the column and to generate a signal in response to variation in its composition due to eluted components. As it transmits physical signal into recordable electrical signal, it is another crucial part of GC. The requirements of a detector for GC are listed below.

Detectors for GC must respond rapidly to minute concentration of solutes as they exit the column, i.e., they are required to have a fast response and a high sensitivity. Other desirable properties of a detector are: linear response, good stability, ease of operation, and uniform response to a wide variety of chemical species or, alternatively predictable and selective response to one or more classes of solutes.

Recording Devices

GC system originally used paper chart readers, but modern system typically uses an online computer, which can track and record the electrical signals of the separated peaks. The data can be later analyzed by software to provide the information of the gas mixture.

How Does GC Work?

Separation Terminology

An ideal separation is judged by resolution, efficiency, and symmetry of the desired peaks, as illustrated by Figure 5.1.4.

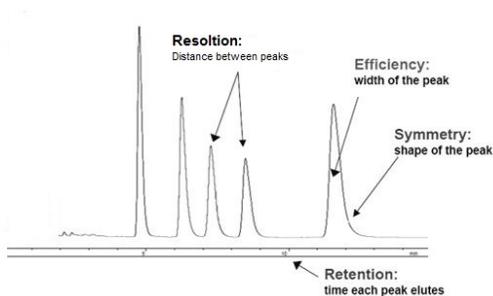


Figure 5.1.4 Separation terminology. Adapted from www.gchelp.tk

Resolution (R)

Resolution can be simply expressed as the distance on the output trace between two peaks. The highest possible resolution is the goal when developing a separation method. Resolution is defined by the R value, 5.1.1, which can be expressed mathematically, 5.1.2, where k is capacity, α is selectivity, and N is the number of theoretical plates. An R value of 1.5 is defined as being the minimum required for baseline separation, i.e., the two adjacent peaks are separated by the baseline. Separation for different R values is illustrated in Figure 5.1.5.

$$R = \text{capacity} \times \text{selectivity} \times \text{efficiency} \quad (5.1.1)$$

$$R = [k/(1+k)](\alpha - 1/\alpha)(N^{0.5}/4) \quad (5.1.2)$$

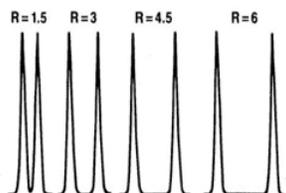


Figure 5.1.5 Different separation resolutions. Adapted from www.gchelp.tk

Capacity (k')

Capacity (k') is known as the retention factor. It is a measure of retention by the stationary phase. It is calculated from 5.1.3, where t_r = retention time of analyte (substance to be analyzed), and t_m = retention time of an unretained compound.

$$k' = (t_r - t_m)/t_m \quad (5.1.3)$$

Selectivity

Selectivity is related to α , the separation factor (Figure 5.1.6). The value of α should be large enough to give baseline resolution, but minimized to prevent waste.

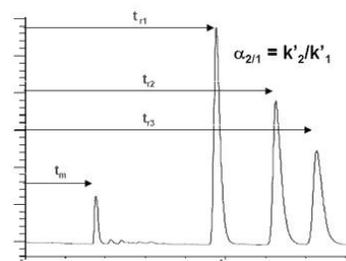


Figure 5.1.6 Scheme for the calculation of selectivity. Adapted from www.gchelp.tk

Efficiency

Narrow peaks have high efficiency (Figure 5.1.7), and are desired. Units of efficiency are "theoretical plates" (N) and are often used to describe column performance. "Plates" is the current common term for N , is defined as a function of the retention time (t_r) and the full peak width at half maximum ($W_{b1/2}$), EQ.

$$N = 5.545(t_r/W_{b1/2})^2 \quad (5.1.4)$$

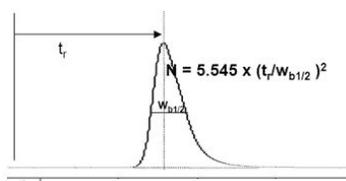


Figure 5.1.7 Scheme for calculating efficiency. Adapted from www.gchelp.tk

Peak Symmetry

The symmetry of a peak is judged by the values of two half peak widths, a and b (Figure 5.1.8). When $a = b$, a peak is called symmetric, which is desired. Unsymmetrical peaks are often described as "tailing" or "fronting".

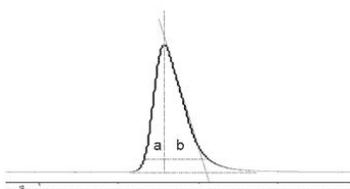


Figure 5.1.8 Scheme for the symmetry of a peak. Adapted from www.gchelp.tk

An Ideal Separation

The attributions of an ideal separation are as follows:

- Should meet baseline resolution of the compounds of interest.
- Each desired peak is narrow and symmetrical.
- Has no wasted dead time between peaks.
- Takes a minimal amount of time to run.
- The result is reproducible.

In its simplest form gas chromatography is a process whereby a sample is vaporized and injected onto the chromatographic column, where it is separated into its many components. The elution is brought about by the flow of carrier gas (Figure 5.1.9).

The carrier gas serves as the mobile phase that elutes the components of a mixture from a column containing an immobilized stationary phase. In contrast to most other types of chromatography, the mobile phase does not interact with molecules of the analytes. Carrier gases, the mobile phase of GC, include helium, hydrogen and nitrogen which are chemically inert. The stationary phase in gas-solid chromatography is a solid that has a large surface area at which adsorption of the analyte species (solutes) take place. In gas-liquid chromatography, a stationary phase is liquid that is immobilized on the surface of a solid support by adsorption or by chemical bonding.

Gas chromatographic separation occurs because of differences in the positions of adsorption equilibrium between the gaseous components of the sample and the stationary phases (Figure 5.1.9). In GC the distribution ratio (ratio of the concentration of analytes in stationary and mobile phase) is dependent on the component vapor pressure, the thermodynamic properties of the bulk component band and affinity for the stationary phase. The equilibrium is temperature dependent. Hence the importance of the selection the stationary phase of the column and column temperature programming in optimizing a separation.

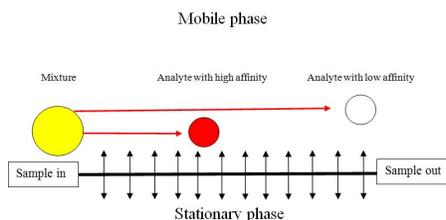


Figure 5.1.9 Scheme for partition in mobile and stationary phases.

Choice of Method

Carrier Gas and Flow Rate

Helium, nitrogen, argon, hydrogen and air are typically used carrier gases. Which one is used is usually determined by the detector being used, for example, a discharge ionization detection (DID) requires helium as the carrier gas. When analyzing gas samples, however, the carrier is sometimes selected based on the sample's matrix, for example, when analyzing a mixture in argon, an argon carrier is preferred, because the argon in the sample does not show up on the chromatogram. Safety and availability are other factors, for example, hydrogen is flammable, and high-purity helium can be difficult to obtain in some areas of the world.

The carrier gas flow rate affects the analysis in the same way that temperature does. The higher the flow rate the faster the analysis, but the lower the separation between analytes. Furthermore, the shape of peak will be also effected by the flow rate. The slower the rate is, the more axial and radical diffusion are, the broader and the more asymmetric the peak is. Selecting the flow rate is therefore the same compromise between the level of separation and length of analysis as selecting the column temperature.

Column Selection

Table 5.1.1 shows commonly used stationary phase in various applications.

Table 5.1.1 Some common stationary phases for gas-liquid chromatography. Adapted from www.cem.msu.edu/~cem333/Week15.pdf

Stationary Phase	Common Trade Name	Temperature (Celsius)	Common Applications
Polydimethyl Siloxane	OV-1, SE-30	350	General-purpose nonpolar phase, hydrocarbons, polynuclear aromatics, drugs, steroids, PCBs
Poly(phenylmethyl-dimethyl) siloxane (10% phenyl)	OV-3, SE-52	350	Fatty acid methyl esters, alkaloids, drugs, halogenated compounds
Poly(phenylmethyl) siloxane (50% phenyl)	OV-17	250	Drugs, steroids, pesticides, glycols
Poly(trifluoropropyl-dimethyl) siloxane	OV-210	200	Chlorinated aromatics, nitroaromatics, alkyl-substituted benzenes
Polyethylene glycol	Carbowax 20M	250	Free acids, alcohols, ethers, essential oils, glycols
Poly(dicyanoallyldimethyl) siloxane	OV-275	240	Polyunsaturated fatty acid, rosin acids, free acids, alcohols

Column Temperature and Temperature Program

For precise work, the column temperature must be controlled to within tenths of a degree. The optimum column temperature is dependent upon the boiling point of the sample. As a rule of thumb, a temperature slightly above the average boiling point of the sample results in an elution time of 2 - 30 minutes. Minimal temperatures give good resolution, but increase elution times. If a sample has a wide boiling range, then temperature programming can be useful. The column temperature is increased (either continuously or in steps) as separation proceeds. Another effect that temperature may have is on the shape of peak as flow rate does. The higher the temperature is, the more intensive the diffusion is, the worse the shape is. Thus, a compromise has to be made between goodness of separation and retention time as well as peak shape.

Detector Selection

A number of detectors are used in gas chromatography. The most common are the flame ionization detector (FID) and the thermal conductivity detector (TCD). Both are sensitive to a wide range of components, and both work over a wide range of concentrations. While TCDs are essentially universal and can be used to detect any component other than the carrier gas (as long as their thermal conductivities are different from that of the carrier gas, at detector temperature), FIDs are sensitive primarily to hydrocarbons, and are more sensitive to them than TCD. However, an FID cannot detect water. Both detectors are also quite robust. Since TCD is non-destructive, it can be operated in-series before an FID (destructive), thus providing complementary detection of the same analytes. For halides, nitrates, nitriles, peroxides, anhydrides and organometallics, ECD is a very sensitive detection, which can detect up to 50 fg of those analytes. Different types of detectors are listed below in Table 5.1.2, along with their properties.

Table 5.1.2 Different types of detectors and their properties. Adapted from teaching.shu.ac.uk/hwb/chemis...m/gaschrn.html

Detector	Type	Support Gases	Selectivity	Detectability	Dynamic Range
Flame Ionization (FID)	Mass flow	Mass flow	Most organic compounds	100 pg	10 ⁷
Thermal Conductivity (TCD)	Concentration	Reference	Universal	1 ng	10 ⁷

Electron Capture (FCD)	Concentration	Make-up	Halides, nitrates, nitriles, peroxides, anhydrides, organometallic	50 fg	10^5
Nitrogen-Phosphorus	Mass flow	Hydrogen and air	Nitrogen, phosphorus	10 pg	10^6
Flame Photometric (FPD)	Mass flow	Hydrogen and air possibly oxygen	Sulphur, phosphorus, tin, boron, arsenic, germanium, selenium, chromium	100 pg	10^3
Photo-ionization (PID)	Concentration	Make-up	Aliphatics, aromatics, ketones, esters, aldehydes, amines, heterocyclics, organosulphurs, some organometallics	2 pg	10^7
Hall electrolytic Conductivity	Mass flow	Hydrogen, oxygen	Halide, nitrogen, nitrosamine, sulphur	-	-

Headspace Analysis Using GC

Most consumer products and biological samples are composed of a wide variety of compounds that differ in molecular weight, polarity, and volatility. For complex samples like these, headspace sampling is the fastest and cleanest method for analyzing volatile organic compounds. A headspace sample is normally prepared in a vial containing the sample, the dilution solvent, a matrix modifier, and the headspace (Figure 5.1.10). Volatile components from complex sample mixtures can be extracted from non-volatile sample components and isolated in the headspace or vapor portion of a sample vial. An aliquot of the vapor in the headspace is delivered to a GC system for separation of all of the volatile components.

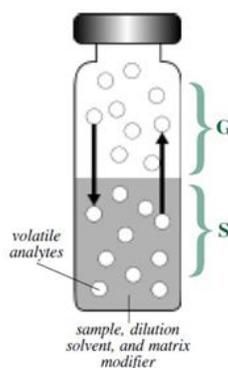


Figure 5.1.10 Schematic representation of the phases of the headspace in the vial. Adapted from *A Technical Guide for Static Headspace Analysis Using GC*, Restek Corp. (2000).

The gas phase (G in Figure 5.1.10) is commonly referred to as the headspace and lies above the condensed sample phase. The sample phase (S in Figure 5.1.10) contains the compound(s) of interest and is usually in the form of a liquid or solid in combination with a dilution solvent or a matrix modifier. Once the sample phase is introduced into the vial and the vial is sealed, volatile components diffuse into the gas phase until the headspace has reached a state of equilibrium as depicted by the arrows. The sample is then taken from the headspace.

Basic Principles of Headspace Analysis

Partition Coefficient

Samples must be prepared to maximize the concentration of the volatile components in the headspace, and minimize unwanted contamination from other compounds in the sample matrix. To help determine the concentration of an analyte in the headspace, you will need to calculate the partition coefficient (K), which is defined by 5.1.5, where C_s is the concentration of analyte in sample phase and C_g is the concentration of analyte in gas phase. Compounds that have low K values will tend to partition more readily into the gas phase, and have relatively high responses and low limits of detection. K can be lowered by changing the temperature at which the vial is equilibrated or by changing the composition of the sample matrix.

$$K = C_s/C_g \quad (5.1.5)$$

Phase Ratio

The phase ratio (β) is defined as the relative volume of the headspace compared to volume of the sample in the sample vial, 5.1.6, where V_s =volume of sample phase and V_g =volume of gas phase. Lower values for β (i.e., larger sample size) will yield higher responses for volatile compounds. However, decreasing the β value will not always yield the increase in response needed to improve sensitivity. When β is decreased by increasing the sample size, compounds with high K values partition less into the headspace compared to compounds with low K values, and yield correspondingly smaller changes in C_g . Samples that contain compounds with high K values need to be optimized to provide the lowest K value before changes are made in the phase ratio.

$$\beta = V_g/V_s \quad (5.1.6)$$

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