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A REVIEW ON DEMONSTRATION OF HPLC

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ABSTRACT

High-Performance Liquid Chromatography (HPLC) is a powerful analytical technique used for separating, identifying, and quantifying components in a mixture. This demonstration aims to showcase the principles and operation of HPLC in a laboratory setting. It involves the use of a liquid mobile phase that is pumped through a column packed with a stationary phase, where the sample mixture is separated based on the differential interactions between the analytes and the stationary phase. The separated components are then detected, typically by UV-Vis absorption or fluorescence, and quantified. This demonstration will highlight key aspects such as sample preparation, column selection, mobile phase optimization, and the role of detector systems in obtaining accurate results. By understanding the setup and operation of an HPLC system, users can effectively apply the technique to a wide range of applications, from pharmaceutical analysis to environmental monitoring.

1.INTRODUCTION

HPLC, developed in the late 1960s by Kirkland and others, integrates liquid chromatography principles into gas chromatography techniques for separating macromolecular substances like proteins and nucleic acids. Using stationary phases with smaller particle sizes under high pressure, HPLC achieves rapid separations within minutes to hours. Its four basic components are a high-pressure infusion system, sample loading system, separation system, and detection system. Today, HPLC is widely used in pharmaceuticals, biotechnology, environmental science, polymers, and the food industry.

Developed in the late 1960s by Kirkland and others, HPLC combines liquid and gas chromatography principles to separate macromolecules like proteins and nucleic acids. It uses small-particle stationary phases under high pressure for rapid separations. Key components include a high-pressure infusion system, sample loader, separation system, and detector. HPLC is widely applied in pharmaceuticals, biotechnology, environmental science, polymers, and food industries.

2.GENERAL PRINCIPLE OF HPLC

The separation principle of High-Performance Liquid Chromatography (HPLC) is based on the distribution of the analyte (sample) between a mobile phase (eluent) and a stationary phase (the packing material in the column). Depending on the chemical structure of the analyte, the molecules are delayed as they pass through the stationary phase. The specific intermolecular interactions between the sample molecules and the packing material determine their "on-column" retention time. As a result, different components of a sample are eluted at different times, achieving the separation of the sample's constituents. A detection unit (such as a UV detector) identifies the analytes as they exit the column. The signals are then processed and recorded by a data management system (software) and displayed in a chromatogram. After passing through the detector, the mobile phase can be directed to additional detectors, a fraction collection unit, or discarded as waste. In general, an HPLC system consists of the following components: a solvent reservoir, a pump, an injection valve, a column, a detector unit, and a data processing unit.

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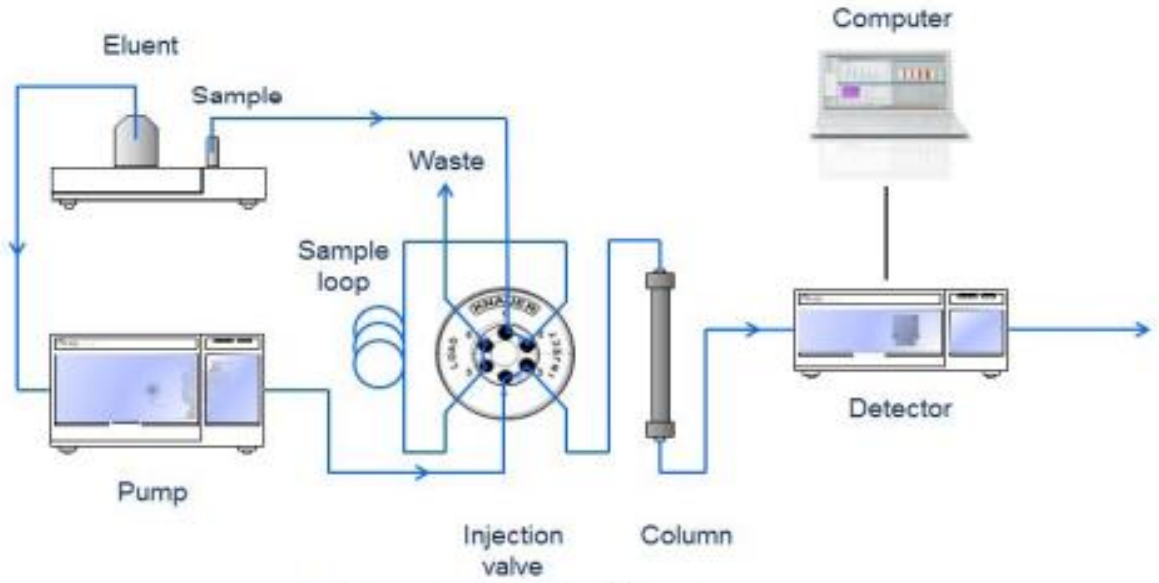
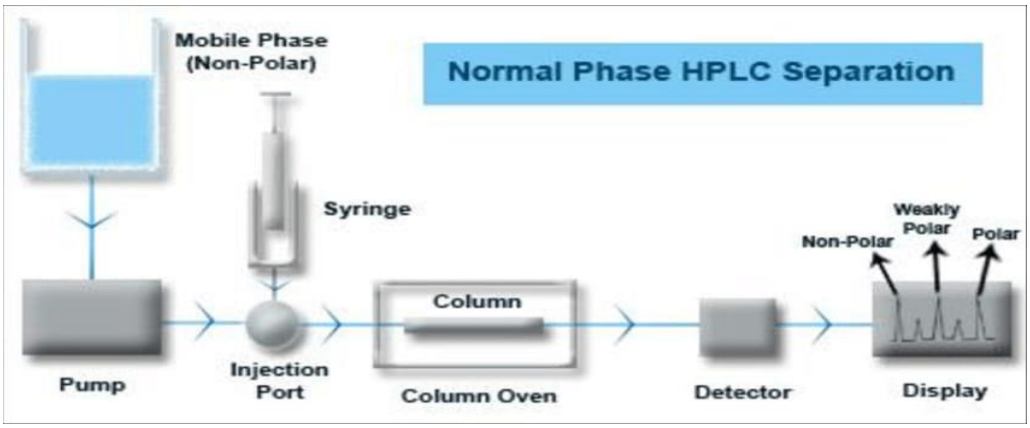


Fig. 1 Schematic layout of a HPLC system

3. TYPES OF HPLC

3.1 Normal Phase Chromatography:

Also known as Normal Phase HPLC (NP-HPLC), this technique separates analytes based on their polarity. It utilizes a polar stationary phase and a non-polar mobile phase. Polar analytes interact with and are retained by the polar stationary phase, with adsorption strength increasing as the analyte's polarity rises. These interactions result in longer elution times for more polar compounds**.**



3.2 Reversed Phase Chromatography

Reversed Phase HPLC (RP-HPLC or RPC) uses a non-polar stationary phase and a moderately polar aqueous mobile phase. The separation occurs through hydrophobic interactions between the non-polar stationary phase and relatively non-polar analytes, driven by the repulsive forces between the analyte and the polar mobile phase. The binding of the analyte to the stationary phase is influenced by the surface area contact between the non-polar part of the analyte and the ligand in the aqueous mobile phase.

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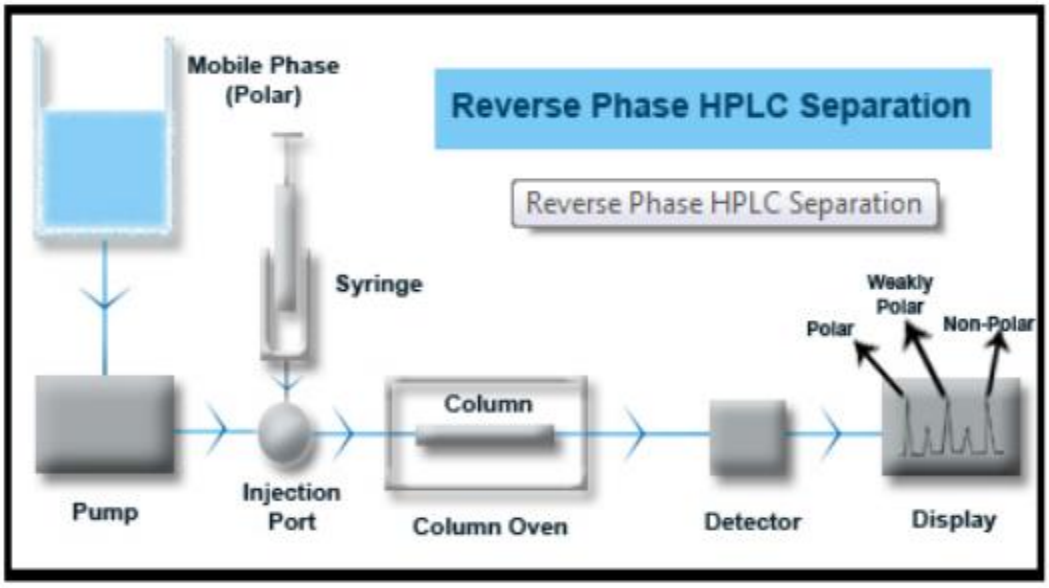
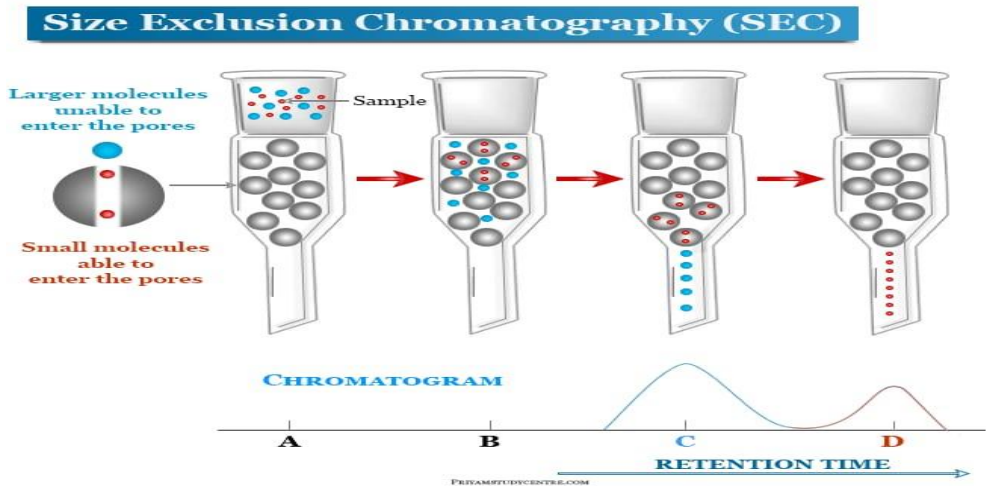


3 3. Size Exclusion Chromatography

Size Exclusion Chromatography (SEC), also known as Gel Permeation Chromatography (GPC) or Gel Filtration Chromatography, primarily separates molecules based on their size. It is commonly used to determine the molecular weight of polysaccharides, and to analyze the tertiary and quaternary structures of proteins and amino acids.



3.4 Ion Exchange Chromatography

Ion Exchange Chromatography relies on the interaction between charged solute ions and oppositely charged sites on the stationary phase. Ions with the same charge as the stationary phase are excluded. This technique is widely used for water purification, protein purification (such as in the isolation of proteins), and high-pH anion-exchange chromatography for carbohydrates and oligosaccharides.

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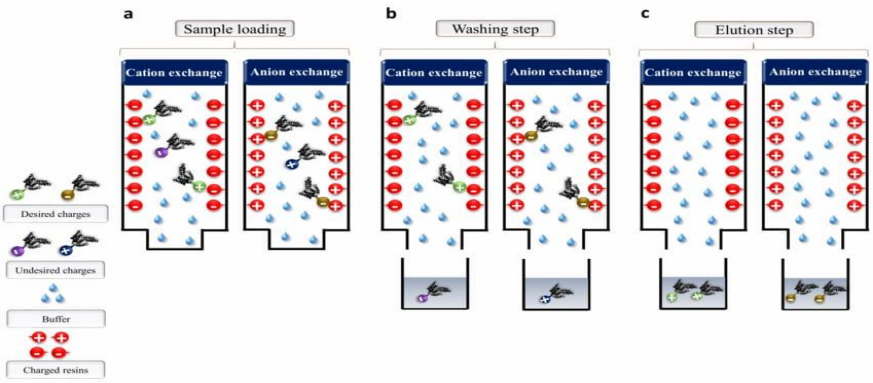


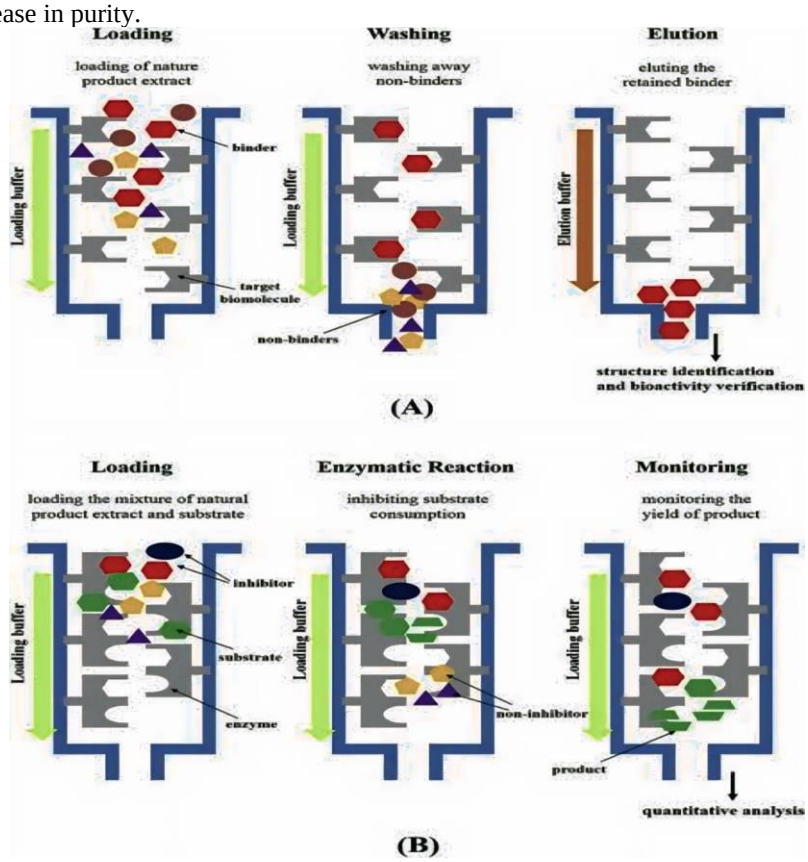
3.5 Bio-Affinity Chromatography

This method separates compounds based on the specific, reversible interactions between proteins and ligands. The ligands are covalently attached to a solid support matrix, which retains proteins that interact with these column-bound ligands. Proteins can be eluted from the column in two ways:

Biospecific Elution: By adding a free ligand to the elution buffer, which competes with the column-bound ligand.

Aspecific Elution: By altering the conditions (e.g., changing pH or salt concentration) to weaken the interaction between the protein and the column-bound ligand.

Due to the high specificity of the interaction, bio-affinity chromatography can achieve significant purification in a single step, often providing a 10- to 1000-fold increase in purity.



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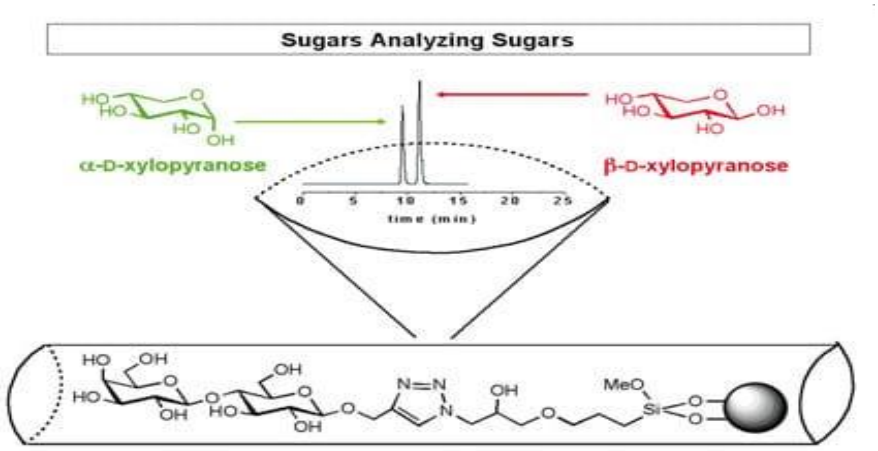
3.6 Hydrophilic Interaction Chromatography (HILIC)

Another chromatographic separation mode used in High-Performance Liquid Chromatography (HPLC) is Hydrophilic Interaction Chromatography (HILIC). This technique combines the principles of hydrophilic interaction liquid chromatography with the conventional HPLC approach. HILIC is specifically applied in certain HPLC columns for specialized analyses. In HILIC, the separation of biomolecules occurs based on their polar and hydrophilic interactions. This mode is particularly effective for the separation of small polar compounds using polar stationary phases.

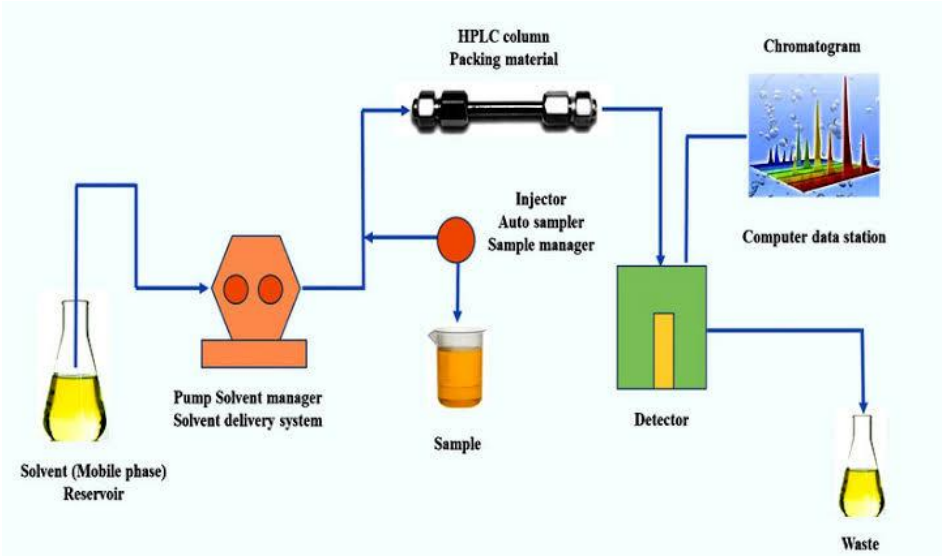


4. INSTRUMENTATION OF HPLC

Components of HPLC

1. Solvent Reservoir and Degassing system
2. Pumping System
3. Sample Injection System
4. Columns
5. Detectors
6. Data Handling System

FIG. High Performance Liquid Chromatography System



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4.1. Solvent reservoir and Degassing system

The mobile phase used in High-Performance Liquid Chromatography (HPLC) can consist of a mixture of organic solvents, an aqueous-organic mixture, or a buffer solution. The choice of mobile phase depends on the chromatographic technique and the type of detector employed. Specially refined commercial-grade solvents, which are purified to remove UV-absorbing impurities and particulate matter, are commonly used in HPLC. If other grades of solvents are considered, purification is essential because impurities, such as those with strong UV absorption, high polarity (e.g., traces of water or ethanol in chloroform), or those that affect the detector, can interfere with the separation process.

The solvent reservoir is typically a 1-liter glass bottle with a lid, connected to a PTFE (polytetrafluoroethylene) tube of 1/8 inch diameter to transfer the mobile phase from the reservoir to the degasser and pump. To avoid irregular pumping, contamination of the column, damage to seals and valves, or column blockages, the liquid entering the pump must be free from impurities like dust and particulate matter. Often, a stainless steel filter (with a pore size of 2 microns) is used in the PTFE tube within the reservoir, or an inline filter is employed to ensure the mobile phase is adequately purified before entering the system.

Degassing System ;

Generally, liquids dissolve some amounts of atmospheric gases (e.g., air or suspended air-bubbles) that cause some major practical problems in HPLC, specifically affecting the working of pump and the detector. These problems can be avoide d by degassing the mobile phase. Degassing is performed by:

1) External Vacuum Degassing
2) Helium sparging
3) Online Degassing
4) Filters

4.1.1 .External Vacuum Degassing

External Vacuum Degassing: In this method, the solvent is placed in a container and exposed to an ultrasonic bath while under vacuum, which is created using a vacuum pump. This process helps to remove dissolved gases from the solvents, making them suitable for use in HPLC. It is particularly effective for solvents that tend to absorb gases, such as carbon dioxide, and is also useful for eluents that are blanketed with an inert gas like helium. This technique is illustrated in the figure.

Fig. Instrumentation OF A Typical HPLC Unit

4.1.2 Helium Sparging

This technique involves bubbling helium through the solvent to remove other dissolved gases. The amount of helium and the duration of sparging need to be carefully controlled. Since helium is insoluble in the mobile phase, it escapes without affecting the chromatographic process. This method, known as helium sparging, can be performed either online, if the helium tank is integrated with the HPLC system, or offline. However, there are some limitations. Helium may selectively volatilize the more volatile solvents, potentially altering the composition of the premixed solvents. Additionally, helium is relatively expensive and requires large quantities for effective sparging.

4.1.3Online Degassing

This technique involves using a vacuum pump in conjunction with the HPLC system. A vacuum is applied to semi-permeable tubes through which the solvents flow, effectively removing dissolved air from the solvents. The expelled air is then directed to a waste collection container. This method is illustrated in the figure.

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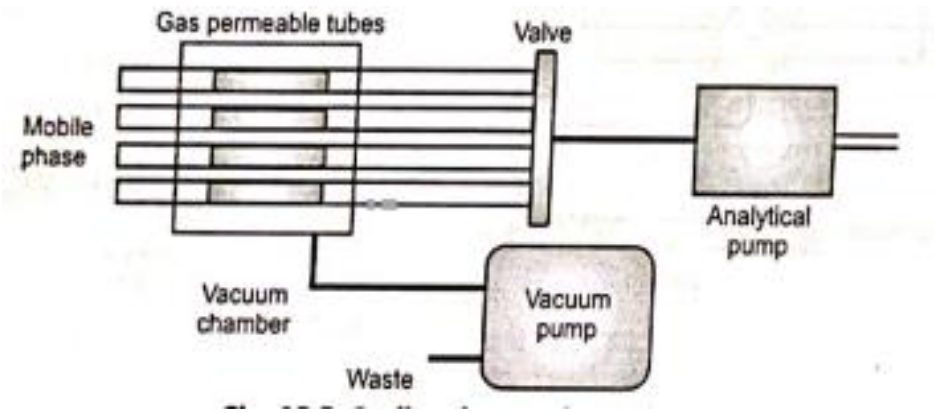

Fig. Online degassschematic

4.1.4 Filtration

In addition to the methods mentioned above, filters are also employed to remove dust and other impurities from solvents. Membrane filters with a pore size of 0.45 µm are commonly used. The mobile phase is filtered through these membranes using a Buchner funnel under vacuum, often followed by ultrasonication.

Other devices that may be used in the process include:
(a) A vacuum pumping system,
(b) A distillation system,
(c) Devices for heating and stirring the solvents, or
(d) A sparging device, where dissolved gases are removed from the solution by passing an inert gas with low solubility through fine bubbles.

Additionally, a filter may be used to remove particulate matter from solvents. An alternative method is to filter the solvent through a Millipore filter under vacuum before it is introduced into the solvent reservoir. The typical pore size for such filters is 0.2 µm, which effectively removes excess particles.

In Analytical HPLC, the mobile phase is pumped through the column at flow rates of 1-5 ml/min. The mobile phase can consist of a mixture of aqueous and organic solvents, or buffer solutions, depending on the chromatographic method and the type of detector used.

4.2 Pumping System

The liquid chromatographic pumps must meet the following requirements:

1. Ability to generate pressures up to 6000 psi (lb/in²),
2. Provide a pulse-free output,
3. Operate with flow rates ranging from 0.1 to 10 ml/min,
4. Achieve flow reproducibility of 0.5% or better,
5. Be resistant to corrosion from various solvents.

Although the high pressures in liquid chromatographic pumps do not pose an explosion risk due to the low compressibility of liquids, solvent leakage from a ruptured component could lead to fire or environmental hazards.

Based on the mechanism of working the pumps can be classified into:
1. Syringe Pump/Displacement pumps
2. Reciprocating piston pumps
3. Constant pressure pumps

4.2.1. **Syringe Pumps**

A syringe pump is made up of a large syringe with a plunger connected to a digital stepping motor or a precision screw drive. As the plunger moves, it pushes a fixed volume of solvent through the chromatograph at a constant, pulseless flow. These pumps are known

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for their smooth, pulseless solvent delivery. The flow rates are typically under 100 µl/min, and the flow is unaffected by viscosity or column back pressure. However, the runtime is limited by the syringe's volume, and no flow occurs during the refill step. It has limitations such as low solvent capacity (200-500ml) and it is not easy to change solvent during gradient elution.

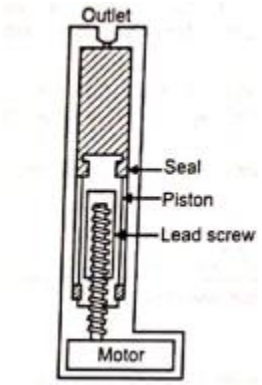

Fig. Syringe Pumps

4.2.2. Reciprocating- piston Pump

A reciprocating pump is one of the most commonly used designs in modern High-Performance Liquid Chromatography (HPLC). Its operation is similar to that of a constant displacement pump. The pump head consists of check valves and a seal-piston assembly. The check valves control the flow of solvents from the reservoir into the pump chamber and then onto the column. The mechanism involves two main strokes: the fill stroke and the delivery stroke. During the fill stroke, the solvent is drawn into the liquid chamber from the solvent reservoir. In the delivery stroke, the piston moves into the chamber, compressing the solvent. As a result, the inlet check valve closes, and when the pressure in the pump head exceeds that in the column, the outlet check valve opens, allowing the mobile phase to flow toward the column.

The advantages of reciprocating pumps include a continuous solvent flow, no limitations on the reservoir size or operating time, and easy and quick solvent changes, which are especially beneficial during gradient elution. These pumps are essential for equipment used in automated operations. A diagram of the reciprocating pump is provided in Fig.

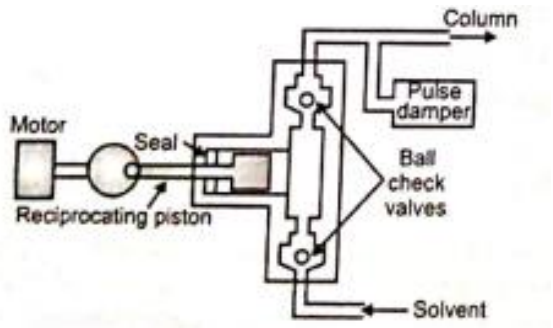

Fig. Reciprocating Piston Pump

4.2.3. Constant Pressure Pumps:

In these pumps, high-pressure gas is introduced into a large piston, which then drives the solvent from the pump chamber to the column. The volume of the solvent chamber is approximately 70 mL (as shown in Fig. 15.9). The pressure exerted on the solvent is proportional to the ratio of the areas of the two pistons, typically between 30:1 and 50:1. As a result, a low-pressure gas source of 1 atm can generate liquid pressures ranging from 1 to 400 atm. To minimize the interference of dissolved gas in the solvent, an intermediate solvent is often used. A valve facilitates the rapid refill of the solvent chamber. This system ensures continuous and pulsation-free pumping, enabling high flow rates, which makes it ideal for preparative applications. It is commonly used for packing columns, though it is less suited for gradient elution due to its limitations in flexibility.

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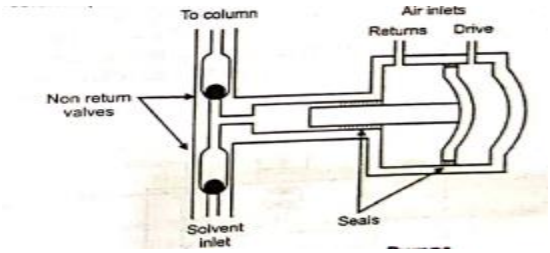


Fig. Constant Pressure Pumps

4.3. Sample Injection System:

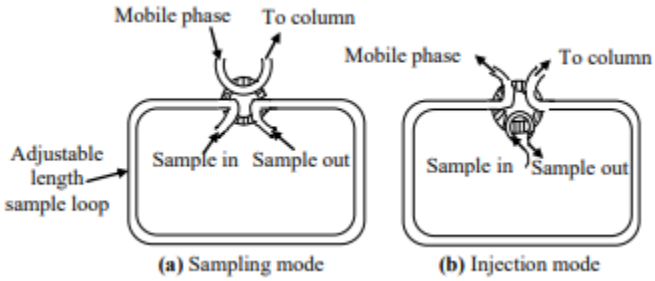
Three primary modes of sample injection are commonly utilized in High-Performance Liquid Chromatography (HPLC):

1. Septum Injectors: In this system, the sample is introduced into the HPLC system through a high-pressure syringe that punctures a self-sealing septum made of elastomer. A significant disadvantage of this method is that the mobile phase comes into direct contact with the septum, leading to a leaching effect. This can result in the appearance of ghost or pseudo peaks in the chromatogram.
2. Stop-Flow, Septum-Less Injection: This method addresses many of the issues associated with septum injectors. The flow of the mobile phase through the column is temporarily halted, and when the column reaches ambient pressure, the top of the column is opened. The sample is then introduced at the top of the column packing. This system is more reliable and still relatively inexpensive compared to other methods.
3. Micro-Volume Sampling Valves: In modern, high-precision HPLC systems, micro-volume sampling valves are used. These valves enable highly reproducible and automated sample injections into pressurized columns with minimal disruption to the mobile phase flow. The operation of these valves is typically described through two modes of sample loop operation:

Sampling Mode
Injection Mode

In the sampling mode, the sample is introduced into an external loop of the micro-volume sampling valve at atmospheric pressure. During the injection mode, the valve rotates, and the sample is injected into the mobile phase. The sample volumes typically range from 2 to 100 µL, although the volume can be adjusted by changing the sample loop or by using variable-volume sampling valves.

This method is particularly advantageous for applications requiring high precision and reproducibility, and it has become standard in modern, automated HPLC systems.



4. 4.Columns

The column is the heart of the chromatograph, providing the means for separating a mixture into components. The selectivity, capacity, and efficiency of the column are all affected by the nature of the packing material or the materials of construction.

- **Column Types in HPLC**

Guard Columns

A guard column is a short column placed between the injector and the analytical column. Although the packing material in both guard columns and analytical columns is similar, the guard column has a larger particle size, which helps reduce the pressure drop.

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The benefits of guard columns include
1. They trap foreign particles and contaminants from the solvents, thereby extending the life of the analytical column.
2. In liquid-liquid chromatography, they help prevent the loss of stationary phase from the analytical column by ensuring the mobile phase is saturated with the stationary phase.

While guard columns and retention gaps are similar in structure (typically 1–10 meters of deactivated fused silica tubing), they serve different functions. Both are connected to the front of the column, but the tubing in a guard column does not contain a stationary phase, and its surface is deactivated to reduce interaction with the solute. A union connects the guard column to the analytical column. The diameter of the guard column or retention gap is typically the same as that of the column, though a larger diameter may be used if necessary.

Guard columns are especially useful for samples that may contain non-volatile residues, which could otherwise contaminate the column. These residues are deposited in the guard column, reducing their interaction with the sample since the guard column does not contain a stationary phase. This prevents contamination of the stationary phase and helps maintain good peak shapes. However, guard columns may require periodic trimming or replacement due to residue buildup. Guard columns are typically 5–10 meters long, which allows for easy trimming before replacement. If peak shape deteriorates, it may indicate the need for trimming or changing the guard column.

- **Retention Gaps**

Retention gaps improve peak shapes for specific samples, columns, and GC conditions. Usually, 3–5 meters of tubing is sufficient to provide the benefits of a retention gap. Retention gaps are particularly useful for large-volume injections (>2 µL) and situations where there is a mismatch in polarity between the solvent and the stationary phase, as seen in splitless, megabore direct, or on-column injections. These conditions can sometimes cause distorted peak shapes.

Polarity mismatches occur when the sample solvent and the column stationary phase have different polarities, leading to issues, especially for peaks near the solvent front or when solutes have similar polarity to the solvent. The benefits of a retention gap are best realized when a guard column is also used in combination with it.

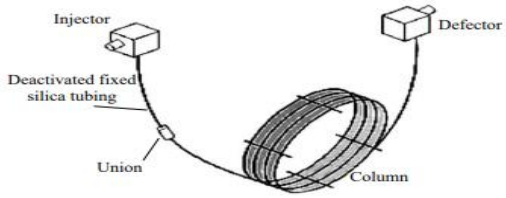

Fig. Retention Gap Or Guard Coulmn

4.4.2 Column Thermostats

Chromatographic procedures can be performed at room temperature without the need for precise control over the column temperature. However, better chromatographic results are achieved when the column temperature is maintained within a few tenths of a degree Celsius. To ensure stable and accurate temperature regulation, water jackets are often installed around the columns. Modern commercial instruments are equipped with heaters that can regulate the column temperature to within a few tenths of a degree, typically ranging from ambient temperature up to 150°C.

5. Detectors

In HPLC, a detector is placed at the end of the system.
Its job is to analyze the solution that comes out of the column.
The concentration of each component in the mixture is directly related to the electronic signal it produces.

- **Features of Detectors Used in HPLC:**

a) The detector should respond to all components in the mixture.
b) The response should be directly proportional to the analyte concentration.
c) The response should not be affected by changes in temperature.
d) The detector should be unaffected by the composition of the eluent (gradient).

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e) It should be able to detect even very low concentrations.
f) The peaks should remain sharp, not broaden.
g) The signal should be stable and reproducible.
h) The detector should be non-destructive.

- **Classification of Detectors**

1. Bulk Property Detectors:
   - Electrical Conductivity HPLC Detector
   - Refractive Index HPLC Detectors
   - Electrochemical HPLC Detectors
   - Light Scattering HPLC Detectors
2. Solute Property Detectors
   - UV/Visible Detectors
   - Fixed Wavelegth Detectors
   - Diode Array Detectors
   - Fluorescence HPLC Detectors

Bulk Property Detectors
Bulk property detectors measure changes in both the solute and the mobile phase together. These detectors often show fluctuations in readings, even with small changes in the mobile phase composition. Examples include refractive index and conductivity detectors. Despite being applicable to many situations, they are used less frequently due to their lower sensitivity and limited range. These detectors are generally referred to as non-selective because they respond to the overall properties of the analyte.

Solute Property Detectors
Solute property detectors, also known as selective detectors, respond to specific physical or chemical properties of the analyte, and ideally, their response is independent of the mobile phase. While it is not entirely possible to achieve complete independence from the mobile phase, the ability of these detectors to discriminate the signal is usually enough to work effectively even when the solvent composition changes, such as in gradient elution.

5.1 Other Popular Detectors Used in HPLC
a) Transport Detectors
Transport detectors use a carrier, such as a metal chain, wire, or disc, which continuously moves through the column, carrying the analyte out of the mobile phase. The solute sticks to the surface of the carrier as a thin film, while the mobile phase evaporates. Two types of transport detectors commonly used in HPLC systems are moving wire and moving chain detectors.

b) Chiral Detectors
Some compounds, especially drugs, can exist as enantiomers, which may have different biological effects. Chiral detectors are designed to detect these different forms of compounds. These detectors are used for optically active substances like amino acids, terpenes, sugars, and other chiral compounds. Techniques like Polarimetry, Optical Rotatory Dispersion (ORD), and Circular Dichroism (CD) are commonly used for chiral detection. ORD detectors work by detecting differences in the refractive index, while CD detectors distinguish enantiomers by measuring the absorption differences of right- and left-handed circularly polarized light.

c) Corona Discharge Detectors
Corona Discharge Detectors (often referred to as Corona Charged Aerosol Detectors, or CAD) are a newer, unique detection method. In this technique, the HPLC eluent is first nebulized using nitrogen (or air) gas to create droplets, which are then dried to remove the mobile phase, leaving behind analyte particles. The principle behind corona discharge detection is the transfer of charge from the analyte particles to a secondary nitrogen (or air) stream. This positively charged stream generates a high voltage in a platinum corona wire, causing diffusion of the particles. The analyte particles are then collected and measured by a sensitive electrometer, which produces a signal directly proportional to the amount of analyte present.

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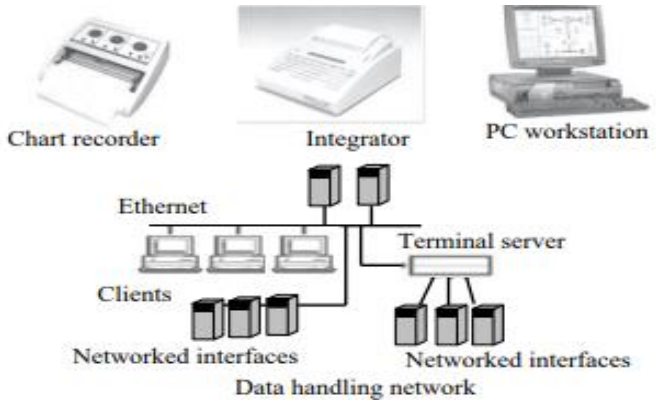
6. Data Handling System

In HPLC, there has been significant progress in data handling systems, evolving from basic devices like strip chart recorders and electric integrators to more advanced setups such as PC-based workstations and modern client-server network systems (the most recent development). Automation and complexity have also improved over time, keeping pace with technological advancements.



7.Advantages And Disadvantages Of HPLC

7.1 Advantages

HPLC has the following advantages:

1) It is a simple, rapid, and reproducible technique.
2) It is highly sensitive.
3) It shows a better performance.
4) It is a rapid process and is less time consuming.
5) Its resolution and separation capacity is high.
6) It is accurate and precise.
7) It utilises a chemically inert mobile and stationary phases.
8) It needs a small amount of mobile phase for developing chamber.
9) It involves early recovery of separated components.
10) It enables easy visualisation of separated components.
11) It shows a good reproducibility and repeatability.
12) It is useful in qualitative and quantitative analysis.
13) It is used for analytical and preparative purposes.
14) It is used for validation and quality control studies of product.

7.2 Disadvantages

The disadvantages of HPLC focus on the detection systems available, and include:

1) The most commonly used detectors in HPLC are UV spectrometers; however, the compound to be analysed should have a UV absorbing chromophore.
2) Variable wavelength UV spectrometers offer versatility but some steroids and other drugs must be derivatized before UV detection.
3) Another slight disadvantage is that the chemically bonded stationary phases applicable in drug analysis should be used within 3 -7 pH range to ensure long term stability.

8.Applications of HPLC

1. Pharmaceutical Industry: HPLC plays a crucial role in the pharmaceutical sector, particularly in Research & Development (R&D), Quality Control (QC), and Formulation & Development (F&D). It is employed for analyzing samples throughout the entire production process, from raw material analysis to final product testing.
   For instance, reverse-phase HPLC is used to analyze polar compounds like polyphenols, steroids, and vitamins, while normal-phase HPLC is suited for non-polar compounds.

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HPLC is primarily used for drug assays, where the chromatographic method is optimized by adjusting factors such as mobile phase composition, pH, flow rate, and column temperature. The method is then validated to ensure its suitability. Additionally, HPLC facilitates multi-component analysis efficiently.

2. Stability Studies: HPLC is widely applied in stability testing of pharmaceutical products. It allows for the comparison of the stability of products with reference standards. Furthermore, the specificity of the analytical method is assessed through degradation studies, including acid, base, oxidation, and photodegradation.
3. Bioanalysis: HPLC is invaluable in bioanalytical studies, particularly for determining drug concentrations in biological samples like blood, plasma, urine, serum, and feces. This makes it essential in pharmacokinetic and bioequivalence studies.
4. Natural Product Analysis: HPLC is essential for the standardization of herbal extracts based on key marker compounds. For example, curcuminoids in turmeric extract and withanolides in Ashwagandha extract can be quantified using HPLC. It is also widely used to standardize polyherbal formulations.
5. Food Analysis: HPLC plays a significant role in analyzing food products, such as testing honey for methylglyoxal content, examining food formulations, and analyzing dairy products. Sugar analysis in food can be carried out using HPLC with a refractive index detector. Additionally, HPLC is used to assess the nutritional content of nutraceuticals, including flavonoids, amino acids, and polyphenols. The choice of column depends on the specific nature of the sample.
6. Drug Interaction Studies: HPLC is valuable in studying drug-drug and herb-drug interactions. By comparing the pharmacokinetic profiles of individual drugs and combinations of herb-drug or drug-drug mixtures in biological samples, HPLC helps predict potential interactions.
7. Preparative Analysis: Preparative HPLC is employed to isolate individual components from a mixture. It is particularly useful for isolating phytoconstituents from herbal fractions following column chromatography.
8. Forensic Sciences: In forensic analysis, HPLC is widely used to identify and quantify substances in biological matrices like blood, plasma, serum, and urine. For example, the presence of morphine can be detected, and in cases of suspected poisoning, HPLC can help identify toxic substances.
9. Cosmetics: HPLC is an important tool in the cosmetics industry for analyzing various cosmetic products, particularly herbal-based ones. Both qualitative and quantitative analyses are carried out using HPLC to determine the active ingredients in these products.

9. CONCLUSION

The conclusion of an HPLC (High-Performance Liquid Chromatography) demonstration typically summarizes the key outcomes and observations from the experiment. It might include the following points:

1. Separation Efficiency: The HPLC successfully separated the components of the sample based on differences in their affinity for the stationary and mobile phases, as evidenced by distinct peaks in the chromatogram.
2. Retention Time: Each compound showed a characteristic retention time, which allows for identification and quantification of the components in the sample.
3. Application: The demonstration highlighted the versatility of HPLC in analyzing complex mixtures, with applications in fields like pharmaceuticals, environmental testing, and food analysis.
4. Instrument Functionality: The HPLC system performed as expected, with the detector providing accurate and reliable readings, and the solvent delivery system maintaining a consistent flow rate.
5. Analysis of Results: The integration of the chromatogram peaks allowed for qualitative and quantitative analysis of the sample, demonstrating the power of HPLC for detailed chemical analysis.

In conclusion, the demonstration provided a clear understanding of HPLC's principles, operation, and its ability to efficiently analyze complex mixtures with high precision and accuracy.

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