Continuously Separation of Sodium and Potassium Using an Adsorption Rotating Disc

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Abstract. This paper is dealing with one of the applications of liquid chromatography using rotary disks. The research aims to study the effect of using distilled water (PH = 7) as a carrier phase and its absence on the practical results using NaOH and KOH at different speeds (2500, 3000, 3500 rpm). As well as choosing the best ratio of the diameter of the rotary disk nozzles that achieves the best displacement between the NaOH and KOH slides with paths separated from each other. Then propose a mathematical model that shows how the thickness of the slice sector behaves with changing the rotational speed. After that, calculating the pressure caused by the rotation and evaluating the results up to a speed of 12000 rpm. The practical results proved that the carrier fluid has an apparent effect on the displacement value between NaOH and KOH slides by changing the internal and external diameters of the rotating disk nozzles and the rotational speed from (500-3500 rpm). The effect of each of them was clear on the displacement of the injected slices from the center of the rotating disk and the convergence between the practical and theoretical results.

Keywords. Rotating disk, Sodium and potassium separation, Carrier phase, Centrifugal separation.

1. Introduction

The rotary disk separation method is an important development of high-performance liquid chromatography methods (HPLC) [1]. It is a laboratory method in which the static medium is in the form of particles of small size and is pushed into the moving medium (liquid) through the column filled with the static medium, using a pump at pressures up to 8000 psi. The pump is used to facilitate the flow of the moving medium through the column at speeds ranging from (5-50ml / min), although the static medium particles are only a few meters in diameter. It has already been possible to obtain flow velocities between (1-4 ml/min) using columns filled with particles of radius up to 5 μm. In this way, compounds that are difficult to volatilization or that are affected by heat can be separated. In this method, it is possible to use fine particles of a solid with absorption properties as a stationary medium or substances with an ionic substitution property and gels with specific pores. A liquid carrier on fine particles of solid material may also be used, as in Figure 1. There are three general methods for preparing static mediums that are suitable for working in this way. Discovering these methods was credited with the rapid spread of their use [1,2,3]. These methods are:
The fluid used as a stationary medium is bonded with a chemical bond with inert solid particles such as the C-Si bond that resists hydration (Hydrolysis). This method is used to load long-chain saturated hydrocarbons and fluorinated ethers into silica gel.

Loading stationary phase as a very thin layer (Pellicular) on the surface of solid matter particles reduces the spread and transmission paths through the stationary medium, and this, of course, increases the speed of the separation process. With this method, it was possible to load the static media in the form of a thin layer of the silica gel material, an ion exchanger, or liquids chemically bound with the outer porous layer. However, a disadvantage of this method is the low capacity of the stationary medium, which requires the use of low concentrations of the sample to ensure that the separation column is not overloaded.

Use of very small radius of column separation to inject materials and leave the rotating disk such as 5, 10, 15, and 20 μm, in which case short columns (10-25 cm) can be used as it has proven that their efficiency is higher and their capacity is greater than the cortical static media. The most important advantages of this method are:

- High accuracy.
- May be used with individually separated materials.
- It can separate highly complex substances such as proteins.
- Small laboratory samples are required.
- It is characterized by high speed.
- It is possible to separate more than one compound at the same time.
- In it, the bromine creol can be used to clarify the slices vision.

Most scientific research focuses on the pharmaceutical industry and how to deal with blood plasma [4,5]. These methods have been used in one principle in work, the hollow, rotating chromatographic column. A group of researchers was able to separate the three amino acids (1,2,3) from each other with the use of a graduated velocity of the spinning column whose highest value reached (800 rpm) [6,7,8,9,10]. In this study, adsorption was accomplished in a rotating disk, and the filling inside it is surrounded by a permeable membrane that allows the passage of materials to be separated with the carrier fluid without the filling components. The nozzles intended to inject the mixture to be separated with the tracer (color substance) are made up of two nozzles that rotate with the rotation of the disk and quite unlike other methods in which the mixture to be separated from one jet is injected.

2. Experimental work

This study suggested the system shown in Figures 1 and 2 for clarifies the difference between it and other methods. As adsorption is accomplished in the rotating disk system, the filling is inside it and is surrounded by a permeable membrane that allows the passage of materials to be separated with the carrying fluid without the filling components. The nozzles intended to inject the mixture to be separated with the tracer (color substance) are made up of two nozzles that rotate with the rotation of the disc, unlike the previous methods, as the difference with the model adopted in the study is that the mixture to be separated is injected from a single fixed nozzle.
Figure 1. A real image of the rotary disk and the slides in the presence of the carrier fluid, which is water, and it consists of 1-The zero line (0 - 0), 2-The deflection of the carrier fluid (water), 3-The injection site of the sodium and potassium water, 4-carrier fluid injection site (water), 5-Sodium and potassium hydroxide exit sites and coloring substance, and 6-Sodium or potassium hydroxide slices and their deviation.

Figure 2. Diagram showing the new design of the proposed rotary adsorption disk compared to the old method. 1-The old rotary hollow chromatography column, 2-Traces the tracer of material A, 3-Traces the tracer of material B, 4- injection nozzles of substances A, B, 5-The zero line (Data line), 6-The deflection angle of material A, 7-The deflection angle of material B.

As for the method of work, the rotary disk is filled with the ion exchange, then the transparent disk is closed from the top, and the system is connected to an electrical source, and upon reaching a different rotational speed, the injection starts from the center of the disk with a mixture of potassium hydroxide and sodium that are to be separated from each other by speed and adsorption. In order to clarify the effect of the presence of the carrier phase (distilled water neutralized with a PH = 7) and its absence, the following ratios were chosen from the diameters ($D_{in}/D_{ex} = 0.333$), ($D_{in}/D_{ex} = 0.416$), ($D_{in}/D_{ex} = 0.5$), ($D_{in}/D_{ex} = 0.666$). Moreover, study the response of each of them under the change of rotational speed (2500, 3000, 3500 rpm). The effect of the presence of the carrier phase helps to deflect slides and
increase their displacement from the normal behavior of a liquid exposed to a high centrifugal force. As the absence of the carrier phase makes the centrifugal force component the predominant component of this force towards the radius of the outer disk, and the displacement amount is lower compared to the presence of a surface that makes it easier for the particles to slide on it and deviate more by the presence of the carrier phase; that is the tangential force component will appear in the presence of the carrier phase [11] and Figure 3 shows this.

![Figure 3. The role of the carrier fluid and how it passes between the filling particles.](image)

3. Mathematical model
In the usual case of circular disk rotation, the relationship between the slice strip thickness (θ °) and the angular rotational speed (ω) is proportional and can be illustrated by the following mathematical equations [12]:

\[ \omega = \frac{d\theta}{dt} \] (1)

\[ d\theta = \omega \times dt \] (2)

Therefore:

\[ \theta = \omega \times t \] (3)

Equation 3 represents the normal rotation of the disk. However, depending on the practical experiments conducted on the new design rotary disk, it was noted that the above relationship is not identical to the work and behavior of the resulting slices of the proposed disk. Therefore, the mathematical equation that achieves the behavior of the slides was due to the change of rotational speed and to the various internal and external diagonals are;

\[ \theta \propto \left[ \frac{1}{\omega \times t} \right] \] (4)

So,

\[ \theta = K \left[ \frac{1}{\omega \times t} \right] \] (5)

Thus,

\[ \theta = \frac{K}{\omega \times t} \] (6)

K is the equation constant and depends on the type of substance and the water solubility value [13,14]. Sinnott et al. were able to calculate the pressure generated and approved for the proposed rotating disk [15];
\[ P_f = 0.5 \times [ \rho_L \times \omega^2 \{ R_{12} - R_{22} \} ] \]  \hspace{1cm} (7)

Where;
- \( P_f \): Centrifugal pressure N/m².
- \( \rho_L \): Liquid density, Kg/m³.
- \( \omega \): Rotational speed of the centrifuge (radian/s).
- \( R_1 \): Inside radius of the bowl, m.
- \( R_2 \): Radius of the liquid surface, m.

Rotating Disk:
- \( R_1 = 8.1 \text{ cm}, \quad R_2 = 1.2 \text{ cm} \)
- \( R_1 = 0.081 \text{ m}, \quad R_2 = 0.012 \text{ m} \)

By taking NaOH solution:
- 10 gm / 9 liter \( H_2O \).

Conc. : \( \frac{10 \text{ gm} \cdot \text{NaOH}}{9 \text{ liter} \cdot \text{H}_2\text{O}} \times \frac{1 \text{ mol}}{40 \text{ g}} = 0.25 \text{ mol NaOH} \).

Then;
- \( 9 \text{ liter} \cdot \text{H}_2\text{O} \times \frac{1 \text{ dm}^3}{1 \text{ liter}} \times \frac{1 \text{ m}^3}{1000 \text{ dm}^3} = 0.009 \text{ m}^3 \text{H}_2\text{O} \).

So;
- \( \rho_{\text{mix}} = \rho_{\text{NaOH}} \times X_{\text{NaOH}} + \rho_{\text{H}_2\text{O}} \times X_{\text{H}_2\text{O}} \)
- \( = 2.1 \text{ g/cm}^3 \times 1\text{Kg/1000g} \times 1000 \text{ cm}^3/1\text{m}^3 \)
- \( = 2.1 \text{ Kg/m}^3 \)

Finally;
- \( P_f = 0.5 \times \rho_L \times \omega^2 \{ R_{12} - R_{22} \} = \frac{1}{2} (722.78) \times \omega^2 (0.006417) \)
- \( P_f = 2.31903963 \times \omega^2 \) \hspace{1cm} (8)

In order to compare the response of the proposed rotary disk with other mathematical models representing other discs, and to note the response of each of them and the relationship of pressure with the rotational speed, the model proposed by Mahmood and Nielsen was referred to [16,17];

\[ p = \frac{\rho \omega^2}{2g(r^2 - r_i^2)} - \rho(r - r_i) \]  \hspace{1cm} (9)

As well as the model proposed by Aphale and a group of researchers is [7];

\[ p - p_o = \frac{6Qh}{\pi b^3} \ln\left(\frac{R_i}{r}\right) + \frac{\rho \omega^2}{8}(r^2 - R_o^2) \]  \hspace{1cm} (10)

All symbols mentioned in Equations 9 and 10 are defined in the Symbols and Terms section.

In Equation (8) is denoted by the letter (U), the proposed by Mahmood and Nielsen is denoted by the letter (V), and the model proposed by Aphale is denoted by the letter (W).

4. Results and discussion

Figure 4 illustrates the effect of changing the rotational speed of the disk by maintaining the ratio between the inner and outer diagonals at \( D_{in}/D_{ex} = 0.333 \). In the presence of the carrier phase, it is observed that the displacement between the two slides increases altogether with the increase in the rotational speed, as shown in Figure 4a, and quite the opposite in the case of no carrier fluid. It can be noticed that the two slices begin to come close to each other with increasing rotational speed, as in Figure 4b, which increases the difficulty of the separation between the two slices.
The effect of the rotational speed on the slice's thickness at $D_{in}/D_{ex} = 0.416$ is shown in Figure 5. It was noticed that the two slices did not get any interference between them, but instead, they came out of two separate paths, as shown in Figure 5a, despite the increase in the rotation speed from (500-3500 rpm). In contrast, it is observed that the slices begin to intersect and converge with each other at high speed, as shown in Figure 5b.

In Figure 6, when $D_{in}/D_{ex} = 0.5$, it is observed in the presence of the carrier phase in Figure 6a that there is a clear response to the change in thickness of the slide with the rotational velocity and the increase in the deflection between the two slides at the speeds 3000 rpm and 3500 rpm. On the other hand, figure 6b shows without the carrier phase the range of slow response of the system so that the thickness of the slices is not affected to a large extent when increasing the rotation.

In Figure 7, when $D_{in}/D_{ex} = 0.666$, it was observed that the two experiments confirm the narrowing of the thickness of the slice with the increase in the rotation speed, but completely opposite in the deviation of the two slides from each other. In the presence of the carrier fluid, Figure 7a, the two slides are moving away from each other, and in the absence of the carrier phase, Figure 7b, the two slides are close to each other with an increase in the rotation speed.

![Figure 4](image-url1)

**Figure 4.** Slice strip thickness when $D_{in}/D_{ex} = 0.333$ with rotational velocity changes (a) With the carrier fluid and (b) Without the carrier fluid.

![Figure 5](image-url2)

**Figure 5.** Slice strip thickness when $D_{in}/D_{ex} = 0.416$ with rotational velocity changes (a) With the carrier fluid and (b) Without the carrier fluid.
Figure 6. Slice strip thickness when $D_{in}/D_{ex} = 0.5$ with rotational velocity changes (a) With the carrier fluid and (b) Without the carrier fluid.

Figure 7. Slice strip thickness when $D_{in}/D_{ex} = 0.666$ with rotational velocity change (a) With the carrier fluid and (b) Without the carrier fluid.

The summary of the discussion for Figures 4, 5, 6, and 7 is in Figure 8, which shows the relationship between the difference in the deflection of both sodium and potassium hydroxide ($\Delta \theta$) at velocity (2500,3000,3500rpm) and the ratio of the inner and outer diameter ($D_{in}/D_{ex}$). The best displacement ratio between the two slices was found at $D_{in}/D_{ex} = 0.416$. From the above results, it was concluded that the presence of carrier fluid is better than without it, especially at high velocity, and that the displacement in the slides of sodium and potassium hydroxide can be observed, and conversely, in the absence of the carrier fluid. The effect of the presence of the carrier fluid helps to deflect the slides and increase their displacement, which is the expected behavior of a liquid that is subjected to a centrifugal force, as the absence of the carrier fluid makes the centrifugal force vehicle towards the disk radius is the predominant component of this force, and the amount of displacement is less compared to the presence of a surface that facilitates the particles have to slip on and deflect further by the presence of the carrier fluid, meaning that the tangential force component will appear in the presence of the carrier fluid.

When changing the outer diameter of the Dex nozzles, which are 36 jets, they are installed on the circumference of the rotating adsorption disc with diameters (0.4 mm, 1mm, 1.25mm, 1.5mm, 1.75mm, 2mm, 2.25mm, 2.5mm and 3mm), with the inner diameter fixed ($D_{in} = 2.25mm$). The practical results were shown in Figures 9 and 10 for each of the sodium and potassium hydroxide strips, so it can be concluded that increasing the rotational speed and the outer diameter of the nozzles means a decrease in the ratio of the inner to the outer diameter ($D_{in}/D_{ex}$) and thus will be reflected in the increase in the displacement of the slices. However, we must bear in mind not to exceed the ideal percentage defined in Figure 5.
Figure 8. The difference in the displacement of the sodium and potassium hydroxide slides from each other and their relationship with $D_{in}/D_{ex}$ in the presence of the carrier fluid.

![Figure 8](image)

Figure 9. The behavior of the potassium hydroxide slide when the inner diameter is $D_{in} = 2.25$mm, and the outer diameter is changed from 0.4mm to 3mm.

![Figure 9](image)

Figure 10. The behavior of the sodium hydroxide slide when the inner diameter is $D_{in} = 2.25$mm, and the outer diameter is variable from 0.4mm to 3mm.

![Figure 10](image)

In Figures 11 and 12, a convergence between the practical results and the mathematical model's response when changing the diameters and the rotational speed is observed. It is noticeable in Figure 13 that the three models (u, v, w) represented by Equations 8, 9, and 10 confirm the same conclusion,
which is that an increase in the centrifugal pressure accompanies the rotational speed, but to varying degrees, and the reason for this is due to the difference in designs and the targets for which the rotary disks are designed.

**Figure 11.** The conformity of both the proposed mathematical model and the practical results of the behavior of the potassium hydroxide slide.

**Figure 12.** The conformity of both the proposed mathematical model and the practical results of the behavior of the sodium hydroxide slide.

**Figure 13.** Comparing the proposed disc response of Equation 8 with the models in Equation 9 and Equation 10.
5. Conclusion
(i) The presence of the carrier fluid helps to deflect the slices and increase their displacement because it forms a surface that makes it easier for the particles to slip on and deflect more, and the absence of the carrier fluid makes the centrifugal force vehicle towards the disk radius the predominant component of this force, so the slices begin to intersect with each other at high speed.
(ii) It was found that the best displacement ratio between the sodium and potassium hydroxide slides in the presence of the carrier fluid was at $D_{in}/D_{ex} = 0.416$, which is the ideal ratio to maintain the centrifugal pressure in the appropriate amount for the separation process.
(iii) Increasing the rotational speed with increasing the value of the outer diameter of the nozzles and when the value of the internal diameter of the nozzles is fixed means a decrease in the ratio of the inner diameter to the outer diameter ($D_{in}/D_{ex}$), which is reflected in the increase in the displacement of the slices, noting that the ideal percentage determined through the results is not exceeded.
(iv) It was observed from the practical results that the thickness of the strip for both NaOH and KOH decreases with the increase in the rotating speed, with the indication that an increase in the centrifugal pressure accompanies the rotational speed, but in different degrees, due to the difference in the designs of the rotating disks, and this is what the mathematical model has proven to be close to practical results.

Nomenclature

| Variable | Description |
|----------|-------------|
| $Q$      | Volumetric flow (m$^3$/s). |
| $P$      | Pressure (Pa) |
| $\omega$ | Angular velocity (rad /s) |
| $P_0$    | Atmospheric pressure (Pa) |
| $\mu$    | Dynamic viscosity (Ns /m$^2$) |
| $\rho$   | Density (Kg/m$^3$) |
| $P_f$    | Centrifugal pressure (N/m$^2$) |
| $H$      | The thickness of the filling used |
| $g$      | Ground acceleration (9.8m /s$^2$) |
| $r$      | Distance from the radius (mm) |
| $r_i$    | Inner radius (mm) |
| $R_o$    | Outer radius (mm) |
| $\theta$ | Represents the thickness of the strip segment and is measured (degrees) |
| $t$      | Time (min) |
| $D_{in}$ | The inner diameter of sodium and potassium hydrate injection (mm) |
| $D_{out}$| The outer diameter of the outer disk spacer $D_{ex}$ (mm) |
| $\text{rpm}$ | Disc rotation per minute (rpm) |
| $\Delta \theta$ | The difference in displacement between the two slides is measured (degree) |
| $R_1$    | Inner radius (mm) |
| $R_2$    | Liquid surface radius (mm) |

6. References
[1] Hayes R, Ahmed A, Edge T and Zhang H 2014 Core–Shell Particles: Preparation, Fundamentals and Applications in High Performance Liquid Chromatography (Journal of Chromatography A) vol 1357 pp 36–52
[2] Brhane K W, Qamar S and Seidel-Morgenstern A 2019 Two-Dimensional General Rate Model of Liquid Chromatography Incorporating Finite Rates of Adsorption–Desorption Kinetics and Core–Shell Particles (Industrial & Engineering Chemistry Research) vol 58 no 19 pp 8296–8308
[3] Rathore AS and Velayudhan A 2003 Scale-Up and Optimization in Preparative Chromatography: Principles and Biopharmaceutical Applications (Marcel Dekker, Inc.)
[4] Modic P, Hribar G and Podgornik A 2020 *A frontal Analysis Combined with a Simultaneous Chromatographic Analysis of Macromolecules Using a Single Chromatographic System* (Journal of Chromatography A) vol 1610 pp 1–9

[5] Blanche F and Wolfgang MJ 2001 Plasmid DNA Purification using Preparative Continuous Annular Chromatography (American Biotechnology Laboratory) vol 19 no 1 pp 42–44

[6] Hiraku K, Takao K and Kaji HM 2006 *U.S. Patent No. 7,063,513* (Washington, DC: U.S. Patent and Trademark Office)

[7] Aphale CR, Cho J, Schultz WW, Yoshioka S L and Hiraki H 2006 *Modeling and Parametric Study of Torque in Open Clutch Plates* (Journal of Tribology) vol 128 no 2 pp 422–430

[8] Herbsthofer R, Bart HJ, Prior A and Wolfgang J 2001 *The Preparative Continuous Annular Chromatographic Reactor (P-CACR)* (Chemie Ingenieur Technik) vol 73 no 6 pp 772–772

[9] Eccles H, Bond G and Emmott JD 2017 *Advanced Reprocessing—The Potential for Continuous Chromatographic Separations* (Journal of Chromatography and Separation Technologies) vol 8 no 1 pp 1–5

[10] Hilbrig F and Freitag R 2003 *Continuous Annular Chromatography* (Journal of Chromatography B) vol 790 no 1–2 pp 1–15

[11] Hoang N, Landolfi A, Girard A, Peate E, Hernandez J, Gaborieau M, Kravchuk O, Guillaneuf R, Guillaneuf Y and Castignolles P 2008 *Separation and Detection by Size-Exclusion Chromatography* (Journal of Chromatography A) vol 1205 no 1–2 pp 60–70

[12] Mezzacappa A 2005 *Ascertaining the Core Collapse Supernova Mechanism* (Annu. Rev. Nucl. Part. Sci.) vol 55 pp 467–515

[13] Yang J, Yu M and Chen W 2015 *Adsorption of Hexavalent Chromium from Aqueous Solution by Activated Carbon Prepared from Longan Seed: Kinetics, Equilibrium and Thermodynamics* (Journal of Industrial and Engineering Chemistry) vol 21 pp 414–422

[14] Singh P, Bahadur J and Pal K 2017 *One-step one Chemical Synthesis Process of Graphene from Rice Husk for Energy Storage Applications* (Graphene) vol 6 no 3 pp 61–71

[15] Sinnott R and Towler G 2019 *Chemical Engineering Design: Six Edition* (Butterworth-Heinemann. chapter) vol 10 pp 581–590

[16] Mahmood A S 2020 *Optimization of Centrifugal Casting Parameters of AlSi Alloy by Using the Response Surface Methodology* (International Journal of Engineering) vol 32 no 11 pp 1516–1526

[17] Nielsen JP 1978 *Pressure Distribution in Centrifugal Dental Casting* (Journal of Dental Research) vol 657 no 2 pp 261–269