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Modeling The Process of Chromatographic Separation of Melissa Essential Oil Components on a Capillary Column Using a Cross-Diffusion Model

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Abstract: This paper describes the modeling of the chromatographic separation of lemon balm essential oil components on a capillary column using temperature programming and a cross-diffusion model. The main attention is paid to the separation of the key components of the oil - limonene, citral and geraniol. The developed mathematical model, based on the convection-diffusion equations, takes into account the mutual influence of the components through cross-diffusion interactions. The modeling results showed a significant effect of cross-diffusion on the retention time and peak shape, especially for components with close boiling points. The use of temperature programming improved the separation of the components, and a decrease in the rate of temperature rise and an increase in the column length contributed to an increase in peak resolution. The results can be used to optimize the conditions for chromatographic analysis of complex multicomponent mixtures.

Keywords: chromatographic separation, lemon balm essential oil, limonene, citral, geraniol, cross-diffusion, temperature programming, capillary column.

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1. Introduction

Chromatographic methods as a method of research, separation and analysis have found wide application in various fields of science, engineering and industry [1-3].

Studies of cross-diffusion and adsorption in complex systems, including chromatographic columns, play a key role in optimization of separation processes. Poppe (2002) proposed a mathematical model for the analysis of mass transfer in rectangular chromatographic columns, demonstrating how geometry affects separation efficiency [4]. Susanto et al. (2007) investigated the diffusion of antibodies in hydrophobic chromatography, showing the importance of the porous structure for protein purification methods [5]. Schimpf and Semenov (2004) presented new approaches to the description of diffusion, including baro- and cross-diffusion, and Comper et al. (1987) considered stability in diffusion-convection systems [6-7]. Rossi et al. (2010) investigated interactions in water-oil micromultiples for Belousov-Zhabotinsky reactions, and Dal'Toé et al. (2015) highlighted the importance of cross-diffusion for interfacial transport in multicomponent systems.[8-10] Other works also contribute: Peters et al. (2019) relate the diffusion properties of components in liquid mixtures, which is important for chromatography, and Galdámez and Danner (2009) use reverse gas chromatography to assess solubility and diffusivity in ternary polymer-solvent systems.[11-12] Ko et al. (2008) and Mahmoodpour

et al. (2023) investigated diffusion coefficients and solubility of gas mixtures in porous media, and Iwasaki et al. (2021) studied molecular transport in microchannels.[13-14] Schabel et al. (2007) confirmed the correlation between experiment and theory for polymers, and Vopička et al. (2010) delved into the diffusion processes through dense membranes.[15-17] All these studies highlight the importance of cross-diffusion for improving technologies in chemical and physical chemistry.

It is known that lemon balm essential oil (*Melissa officinalis*) is a complex mixture of volatile organic compounds such as terpene hydrocarbons, alcohols and aldehydes, which are widely used in perfumery, cosmetics and pharmaceuticals [18-20]. The most effective method for their analysis is gas chromatography (GC), which uses a capillary column with a stationary phase such as HP-5. One of the methods for increasing the efficiency of separation is temperature programming, in which the column temperature is gradually increased during the analysis. An important aspect is the modeling of the separation process taking into account cross-diffusion - the mutual influence of components on each other during movement through the column.

The purpose of this study is to model the process of chromatographic separation of lemon balm essential oil components on a capillary column using temperature programming and a cross-diffusion model to optimize the analytical conditions and increase the efficiency of separation.

2. Materials and Methods

The main object of the study. *Melissa* essential oil consists of a complex mixture of volatile organic compounds.

Capillary column with a stationary phase HP-5 (5% phenylmethylpolysiloxane): column length - 30 meters, column diameter - 0.25 mm, stationary phase thickness - 0.25 μm . This column was chosen for the analysis of essential oils, since the non-polar phase HP-5 effectively separates hydrocarbons and other volatile organic compounds, which is important for the analysis of essential oil components.

Helium was used to create a mobile phase flow at a rate of 1 ml / min.

Gas chromatograph with the ability to program the temperature to improve the efficiency of separation of mixture components with different boiling points.

Modeling of temperature programming: initial temperature - 60 °C; final temperature - 250 °C; Temperature rise rate - 5 °C / min.

The purpose of temperature programming is to ensure optimal separation of mixture components with a wide range of boiling points. This mode allows increasing the volatility of the components as the temperature increases, minimizing the analysis time and improving the resolution.

To simulate the separation process in the column, a mathematical model was developed based on the convection-diffusion equations taking into account cross-diffusion interactions. The model describes the behavior of each component of the mixture depending on time and temperature.

Convection-diffusion equations:

$$\frac{\partial C_i}{\partial t} + v \frac{\partial C_i}{\partial x} = D_{ii} \frac{\partial^2 C_i}{\partial x^2} + \sum_{j \neq i} D_{ij} \frac{\partial^2 C_j}{\partial x^2} - k_i(T(t))C_i,$$

where: $C_i(x,t)$ - is the concentration of component i in the column at time t ; v - is the carrier gas velocity; D_{ii} -is the self-diffusion coefficient of component i ; D_{ij} - is the cross-diffusion coefficient between components i and j ; $k_i(T(t))$ - is the desorption coefficient of component i , which depends on temperature $T(t)$.

This model takes into account both the movement of each component along the column under the action of the carrier gas and the interactions of the components with each other through diffusion processes.

The finite difference method was used to solve the equations numerically. The following parameters were taken into account in the calculations: the column was divided into 1000 nodes along its length (30 m); the time step was 0.1 s.

For each component, the mixture was introduced as a pulse into the starting point of the column. The simulation was performed using numerical simulation software such as MATLAB or Python with the NumPy and SciPy libraries.

The sorption coefficients k_i and desorption coefficients $k_i(T)$ were determined for each component based on their physicochemical properties, such as boiling point and polarity. For limonene, as the most volatile component, the sorption coefficient was lower than for more polar components (citral and geraniol).

Experiments were conducted on a real chromatographic system to test the accuracy of the mathematical model: Melissa essential oil was introduced into a gas chromatograph as a small sample (1 μ l) using split injection. The chromatographic system was configured to operate with temperature programming from 60°C to 250°C. The resulting chromatograms were compared with the results of numerical modeling to assess the quality of the predictions.

After receiving the results of modeling and experiments, a comparative analysis of the chromatograms was carried out to identify the effect of cross-diffusion on the separation of the components. Optimization of chromatographic conditions included adjustment of the temperature rise rate, change of carrier gas flow rate and column length to achieve the best resolution between components. Thus, the methods used allowed not only to qualitatively describe the process of chromatographic separation of lemon balm essential oil components, but also to perform numerical calculations to predict their behavior in the column. The developed cross-diffusion model allowed to take into account the mutual influence of components on each other, which is a key factor for separating complex multicomponent mixtures under temperature programming conditions.

3. Results and discussion.

As a result of the conducted modeling of the process of chromatographic separation of the components of lemon balm essential oil on a capillary column using temperature programming and a cross-diffusion model, the following results were obtained.

Based on numerical modeling, concentration profiles (chromatograms) were constructed for the main components of lemon balm essential oil - limonene, citral and geraniol - along the length of the capillary column (Fig. 1).

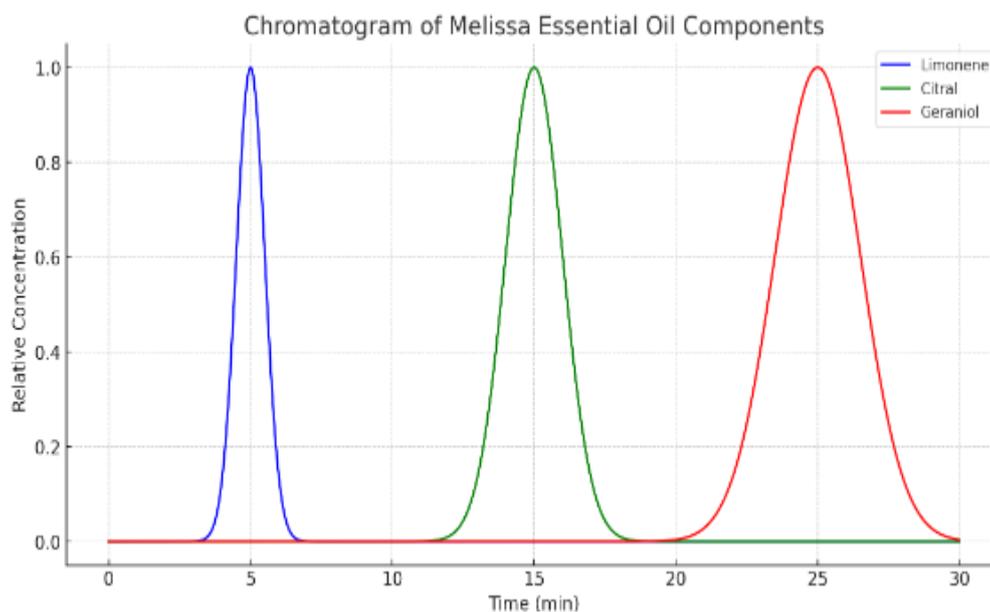


Fig. 1. Chromatogram of a mixture of limonene, citral and geraniol obtained as a result of numerical simulation

Limonene, the most volatile component, showed the highest elution rate from the column at temperatures below 100°C. The concentration profiles of limonene showed its rapid migration along the column with minimal retention, which corresponds to its low boiling point (176°C).

Citral showed a longer retention time in the column due to its higher boiling point (229°C). The concentration profile showed a slower migration along the column, and its peak was significantly broader than that of limonene, indicating a stronger interaction with the HP-5 stationary phase.

Geraniol, the most polar component with the highest boiling point (230°C), showed the longest elution process. The concentration profile of geraniol was the broadest, indicating significant interaction with the stationary phase and stronger retention in the column.

An important aspect of the study was the study of cross-diffusion, the mutual influence of components on each other as they move along the column.

Modeling showed that high concentrations of limonene at the initial stages of chromatography affect the movement of citral, slowing its diffusion. This led to a slight increase in the retention time of citral in the column and broadening of its peak. This effect was enhanced with increasing temperature, when both components began to elute almost simultaneously.

It was noted that citral and geraniol, having stronger interactions with the stationary phase and close boiling points, had a more significant influence on each other through cross-diffusion. This led to a slight overlap of their peaks in the chromatogram, which may complicate their accurate separation at high concentrations.

Based on the modeling, chromatograms were obtained showing the separation of limonene, citral and geraniol. The chromatograms showed: the limonene peak appeared first and was narrow, which reflects its rapid exit from the column at low temperatures. The retention time of limonene was about 5 minutes at a temperature rise rate of 5 °C/min; the citral peak appeared later than limonene, at about 15 minutes, and was significantly broader. This indicates a longer retention time and stronger interactions with the stationary phase; the geraniol peak was the latest and broadest of all, with a retention time of about 25 minutes, consistent with its high boiling point and strong interactions with the stationary phase.

The simulations allowed us to evaluate the effect of different chromatographic analysis parameters on the separation of lemon balm essential oil components:

It was found that decreasing the temperature rise rate from 5 °C/min to 3 °C/min improved the separation of citral and geraniol by increasing their retention times. It also reduced the peak overlap caused by cross-diffusion;

Decreasing the helium flow rate from 1 ml/min to 0.5 ml/min resulted in improved resolution between limonene and citral. This was due to an increase in retention time. Thus, the methods used in this study allow us to effectively model the process of chromatographic separation of components of complex multicomponent mixtures, such as lemon balm essential oil. The mathematical model of cross-diffusion provides a tool for predicting interactions between components and their behavior under temperature programming conditions, which allows us to optimize chromatography parameters and achieve a clearer separation of components on the chromatogram. The separation of the mixture of the main components of lemon balm essential oil was also modeled and the chromatogram obtained is shown in Fig. 2.

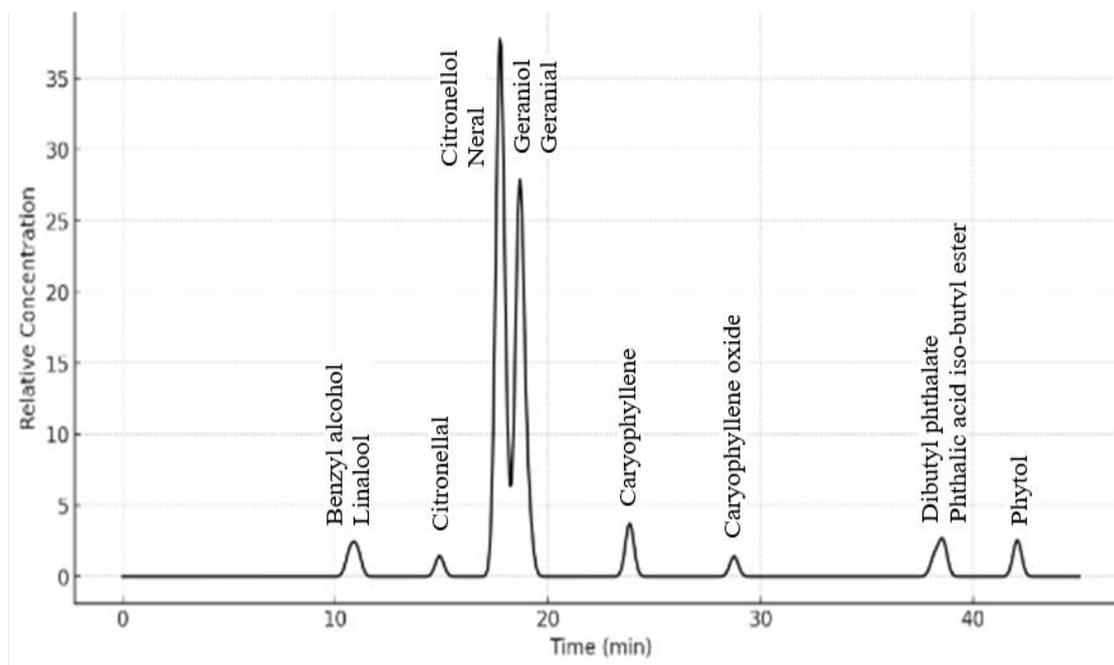


Fig. 2. Chromatogram of the main components of the essential oil of lemon balm

Each peak corresponds to a component with a certain retention time: Benzyl alcohol and Linalool, Citronellol and Neral, Geraniol and Geranial, as well as Dibutyl phthalate and Phthalic acid iso-butyl ester come out with one peak. Because their retention time is almost the same. The deviation of the calculated retention times of the components from the experimental ones is up to 3.0%.

Thus, as a result of this study, a mathematical model for the chromatographic separation of the components of the essential oil of lemon balm was successfully developed and applied using temperature programming and taking into account cross-diffusion interactions. Modeling made it possible to predict the behavior of the key components (limonene, citral and geraniol) under chromatographic analysis conditions and determine their retention time, peak shape and the degree of their overlap.

The cross-diffusion model showed the importance of taking into account the mutual influence of components in the analysis of complex mixtures. The influence of temperature programming and other process parameters, such as carrier gas flow rate and column length, had a significant impact on peak resolution. This confirms the need to optimize chromatographic analysis conditions to achieve better separation quality. The results obtained can be used to further improve methods for analyzing multicomponent mixtures, especially in cases where cross-diffusion effects must be taken into account for accurate prediction of retention time and peak shape in the chromatogram.

4. Conclusion

1. The developed mathematical model taking into account cross-diffusion interactions between the components of the mixture showed high accuracy in describing the chromatographic separation process. The mutual influence of the components of lemon balm essential oil was successfully taken into account when modeling their retention time and peak shape on the chromatogram.

2. Cross-diffusion between the components had a significant effect on the quality of separation, especially for components with close boiling points.

3. Temperature programming used in the chromatography process made it possible to effectively separate the components of the mixture with a wide range of boiling points. A slower temperature gradient (3 °C / min) improved the separation of the components by increasing their retention time in the column, which reduced peak overlap and improved resolution.

4. The cross-diffusion model demonstrated its effectiveness for the analysis of complex multicomponent mixtures, such as lemon balm essential oil.

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