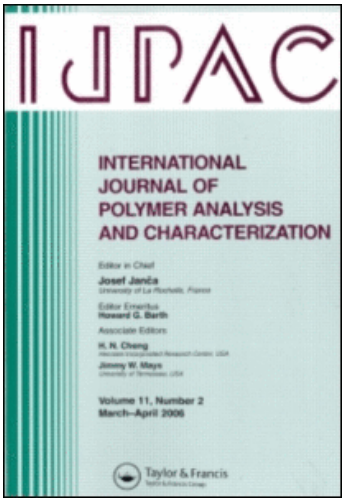

International Journal of Polymer Analysis and Characterization
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713646643

On the Limits of High-Speed Microthermal Focusing Field-Flow Fractionation

Josef Janča[a]; Věra Halabalová[b]; Vladimír Polášek[c]; Martin Vašina[a]; Anastasia Yu. Menshikova[d]
[a] Faculty of Technology, Department of Physics and Materials Engineering, Tomas Bata University, Zlín, Czech Republic [b] Faculty of Technology, Department of Biochemistry and Food Analysis, Tomas Bata University, Zlín, Czech Republic [c] Faculty of Applied Informatics, Department of Mathematics, Tomas Bata University, Zlín, Czech Republic [d] Institute of Macromolecular Compounds, Russian Academy of Sciences, St. Petersburg, Russia

Online publication date: 16 April 2010

To cite this Article Janča, Josef , Halabalová, Věra , Polášek, Vladimír , Vašina, Martin and Menshikova, Anastasia Yu.(2010) 'On the Limits of High-Speed Microthermal Focusing Field-Flow Fractionation', International Journal of Polymer Analysis and Characterization, 15: 3, 191 — 197
To link to this Article: DOI: 10.1080/10236661003681214
URL: http://dx.doi.org/10.1080/10236661003681214

International Journal of Polymer Anal. Charact., 15: 191–197, 2010

ISSN: 1023-666X print
DOI: 10.1080/10236661003681214

Taylor & Francis
Taylor & Francis Group

Short Communication

ON THE LIMITS OF HIGH-SPEED MICROTHERMAL FOCUSING FIELD-FLOW FRACTIONATION

Josef Janča,[1] Věra Halabalová,[2] Vladimír Polášek,[3] Martin Vašina,[1] and Anastasia Yu. Menshikova[4]

[1]*Faculty of Technology, Department of Physics and Materials Engineering, Tomas Bata University, Zlín, Czech Republic*
[2]*Faculty of Technology, Department of Biochemistry and Food Analysis, Tomas Bata University, Zlín, Czech Republic*
[3]*Faculty of Applied Informatics, Department of Mathematics, Tomas Bata University, Zlín, Czech Republic*
[4]*Institute of Macromolecular Compounds, Russian Academy of Sciences, St. Petersburg, Russia*

The migration of microparticles exposed to gravitational-buoyancy force and lift force and transported by the flow of the carrier liquid inside microfluidic conduits was studied from the viewpoint of the transient period (the relaxation) between the moment at which the particles start to be transported by the hydrodynamic flow and the time at which they are focused at an equilibrium position. Relaxation times were calculated theoretically by the incremental numerical method and the results were compared with the experimental data obtained on two microfluidic channels of different lengths and for different average linear velocities of the carrier liquid. It has been found that the maximal linear velocity of the carrier liquid in a microthermal field-flow fractionation channel whose dimensions were already optimized is of the order of a few cm/s under the investigated experimental conditions. At this velocity, the contribution of the secondary relaxation time is negligible compared to the retention time of the micrometer-sized particles.

***Keywords*:** Field-flow fractionation; Focusing; Microfluidic conduit; Microparticles; Optimization; Relaxation; Separation

INTRODUCTION

Microfluidic systems are intensively developed and extensively applied for the fractionation and characterization of nanometer- and micrometer-sized particles (see, for example, Di Carlo et al.[1–3] and references cited therein). A microfluidic device devoted to the separation of the particles, the ultra-microthermal field-flow

Submitted 4 January 2010; accepted 6 February 2010.
Correspondence: Josef Janča, Faculty of Technology, Department of Physics and Materials Engineering, Tomas Bata University, Nad Stráněmi 4511, 760 05 Zlín, Czech Republic. E-mail: jjanca@ft.utb.cz

fractionation unit, was proposed recently.[4] It can be applied for the characterization of biological cells and sub-cellular particles,[5] especially in medical and environmental analyses. Nevertheless, synthetic polymer particles can also be separated and characterized by this technique, and several applications were already demonstrated.[6,7]

This kind of analysis should not be time-consuming. On the other hand, high-performance separation must not be sacrificed in high-speed operation. Whenever the size of the separated species is within the range of roughly 200 nanometers to several micrometers, a focusing mechanism may occur, which is based on the coupling of the inertial lift force,[8–12] gravitation-buoyancy force, and thermodynamic force generated by the imposed temperature gradient.[6,13,14] The lift force, which emerges at high flow rates of the carrier liquid, must be counteracted by other effective forces in order to produce an efficient focusing mechanism. A full utilization of the focusing mechanism in a microfluidic separation unit such as the microthermal field-flow fractionation channel requires careful optimization of the experimental conditions because an unsuitably chosen combination of microfluidic channel length versus carrier liquid flow rate can have disastrous consequences on the performance of the separation.

THEORY

The optimization problem to solve is schematically explained in Figure 1. The particles of a sample analyzed by microthermal field-flow fractionation must start their elution inside the rectangular cross-section channel from one of the main channel walls. This condition is imposed by the action of the effective driving force $F_{eff}(x)$ displacing the particle across the channel thickness (this means along the x-axis) during the focusing. The force $F_{eff}(x)$ is the sum of several forces:

$$F_{eff}(x) = \pm F_{LF}(x) \mp F_G \mp F_{TD} \mp F_f(x) \tag{1}$$

The particular forces acting on a sole spherical particle moving freely in a laminar horizontal flow of a carrier liquid inside a rectangular cross-section channel are: lift force $F_{LF}(x)$, which is due to the fact that the particle is exposed to the velocity gradient in the parabolic flow velocity profile formed between the walls and whose magnitude is proportional to several operational parameters, among them average linear velocity of the carrier liquid; the force F_G, which results from the action of the gravitation and buoyancy; the thermodynamic force F_{TD}, which is due to the imposed temperature gradient generating the thermal diffusion of the particle; and the force of friction $F_f(x)$, which opposes the transverse movement (in the direction of the x-axis) of the particle during the focusing. The forces F_G and $F_{LF}(x)$ can be negative and positive, respectively (with regard to the origin $x = 0$ and positive direction of the x-axis), or vice versa, correspondingly to the sedimentation or flotation, respectively, of a particle in a carrier liquid. At dynamic equilibrium, the driving force is zero, $F_{eff}(x_{eq}) = 0$, and the particle reaches its equilibrium position x_{eq} at which it is focused and is further transported by the carrier liquid flow along the channel at this x_{eq}. Different particles are focused at different x_{eq} positions and are transported along the channel at different linear velocities corresponding to

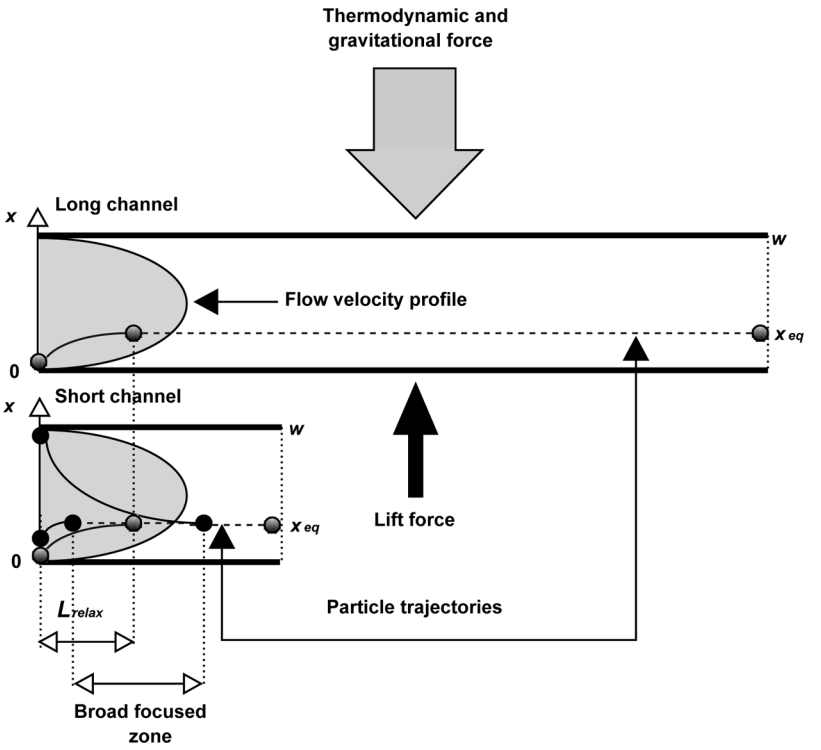

Figure 1. Schematic representation of the trajectories of the particles undergoing the focusing caused by the counteracting gravitational and lift forces in long and short microfluidic channels. The particles, which start their elution caused by the hydrodynamic flow of the carrier liquid from the position $x = 0$ at the accumulation wall (gradual grey points in both channels), reach an equilibrium position x_{eq} at a same distance L_{relax} in both channels under otherwise identical experimental conditions. On the other hand, if the particles are randomly distributed across the channel after the injection (black as well as gradual grey points in the short channel) and the primary relaxation during which they are concentrated by the thermodynamic and gravitational force at the accumulation wall with the flow of the carrier liquid stopped is not applied, the particles run different trajectories and reach the position x_{eq} at different longitudinal distances from the starting point. Consequently, the focused zone is broadened in the direction of the flow, resulting in a decrease of resolution of the zones focused at different x_{eq} positions.

different streamlines of the flow velocity profile formed inside the channel. As a result, different particles elute from the channel at different times and are thus separated.

It has been mentioned above that the important condition to achieve high-performance (high-efficiency) separation is that the starting position of the particles injected at the beginning of the channel must be at one of the main channel walls (accumulation wall). Since in most cases the particles exhibit higher density than the carrier liquid, and temperature gradient generates their transport to the cold (lower) channel wall, the particles are initially concentrated at this wall. It is thus useful to establish an experimental procedure that allows all particles to reach the initial position at the accumulation wall. It can be done, for example, by stopping the flow of the carrier liquid during this concentration process of the particles at the accumulation wall. This stop-flow time is called primary relaxation time, t_{relax1}.

Thereafter, the flow of the carrier liquid is restarted, and all particles are displaced in the direction of the x-axis to their equilibrium position x_{eq} by the action of the driving force $F_{eff}(x)$ and are simultaneously transported by the flow along the channel. The time elapsed between the initial position of the particles at the accumulation wall and equilibrium position x_{eq} is called secondary relaxation time, t_{relax2}. During $t_{relax}2$, the particles run the distance L_{relax} along the channel, as shown in Figure 1.

If the primary relaxation with the flow of the carrier liquid stopped is not applied and the focusing of the particles (secondary relaxation) proceeds during the elution, the particles distributed randomly across the channel after the injection run different trajectories to reach the same x_{eq} position, as schematically demonstrated in Figure 1. Consequently, an individual focused zone is broadened in the direction of the flow, and the resolution of different focused zones is lower.

It is a well-known fact[6] that the efficiency of the channel, measured by the theoretical plate height, increases with decreasing channel thickness w under otherwise identical experimental conditions. Nevertheless, it has been demonstrated previously[4] that the miniaturization of the channel is not unlimited. The thickness w must be chosen with regard to the size of the separated species, which can be of the order of micrometers. An optimal w is approximately 100 μm.[6] A minimum aspect ratio (width to thickness) of the channel is about 20 provided that a special hydrodynamic splitting at the channel input is adopted.[15] If the width and thickness of the channel are optimized with regard to the requirements mentioned above, the length of the channel is imposed by the necessity to inject a detectable quantity of the sample, which itself is determined by the concentration and the injected volume. In order to make the contribution to the zone broadening caused by the injected volume, detector, and all connecting capillaries negligible in comparison to the broadening that is due to the separation and dispersion processes inside the channel, the injected volume of the sample should not exceed about 10% of the volume of the channel.[6] As a result, with regard to the mentioned conditions, the minimal length of the microfluidic channel should be between 50 mm and 100 mm.

It is obvious from Figure 1 that for a given average linear velocity of the carrier liquid, the relaxation distance L_{relax} should be independent of the channel length if the other sizes (width and thickness) are the same. Thus, having all three dimensions of the channel minimized on an acceptable level by respecting the above-mentioned conditions related to the high-performance separations, the question to be discussed is the maximal linear velocity of the carrier liquid still allowing the focused particulate species to reach their equilibrium positions and thus to perform high-speed but also high-performance separations. This problem was studied theoretically and experimentally and the preliminary results are presented in the following section.

MODEL CALCULATIONS, EXPERIMENTS, AND PRELIMINARY RESULTS

The relaxation time of the secondary relaxation process that takes into account the contributing forces included in Equation (1) can be calculated from:

$$t_{relax2} = \int_{r_p+\delta_1}^{x_{eq}-\delta_2} \frac{dx}{v_{relax2}(x)} \tag{2}$$

where $v_{relax2}(x)$ is the velocity of the transverse migration of a particle during the secondary relaxation and r_p is particle radius. The constants δ_1 and δ_2 in the integration limits of Equation (2) are chosen arbitrarily. The value of δ_1 is estimated to be a fraction of r_p by supposing that a steep increase of the $v_{relax2}(x)$ at the takeoff and beginning of the particle transverse movement is short, followed by a deceleration governed by the forces included in Equation (1). Different values of δ_2 can be chosen as fractions of the x_{eq} to investigate the variation of the calculated relaxation time as a function of the distance of the particles from the equilibrium position.

Since the force of friction $F_f(x)$ depends on the local velocity $v_{relax2}(x)$, an incremental numerical calculus must be applied. The details will be published later.

Short microthermal field-flow fractionation and roughly seven times longer standard thermal field-flow fractionation channels were used in the experiments. Their thicknesses w were identical. The retention times of the micrometer-sized polystyrene-based latex particles ($r_p \approx 2.5\,\mu m$) were measured at different linear velocities of the carrier liquid, imposing quite a strong action of the lift forces and thus the focusing mechanism. The gravitational force F_G acting on micrometer-sized particles was strong enough to counterbalance the lift force $F_{LF}(x)$. Consequently, temperature gradient generating the thermodynamic force F_{TD} was not applied in the experiments because the comparison of our theory with the experimental data would be more complicated due to the non-parabolic flow velocity profile formed inside the channel under non-isothermal and thus non-isoviscous conditions.

The comparison of the theoretically calculated secondary relaxation times for a series of different linear velocities of the carrier liquid with the experimental retention times obtained by using two different length channels is presented in Table I. It can be concluded from the data in Table I that the theoretically calculated t_{relax2} is negligible compared with the experimental retention time obtained for the lowest linear velocity of the carrier liquid on the short as well as on the long channel. At medium linear velocity, t_{relax2} is still acceptable compared with the experimental

Table I. Theoretical secondary relaxation times and the experimental retention times calculated and measured, respectively, for polystyrene latex particles in short and long channels as a function of average linear velocity of the carrier liquid

Linear velocity of the carrier liquid (cm/s)	Theoretical t_{relax2} (s)	Experimental retention time[a] (s)
Short channel		
0.26	0.54	168
0.43	2.84	92
0.87	13.88	42
Long channel		
0.20	0.22	503
0.42	2.94	281
0.83	17.37	121

[a]Retention time is calculated from the total time spent inside the channel by the particles from which the injection time and stop-flow time are deduced.

retention time obtained on the short channel and fully acceptable on the long channel. At the highest linear velocity of the carrier liquid, t_{relax2} is too long to be acceptable in comparison with the experimental retention times obtained on both channels.

The comparison of the theoretically calculated t_{relax2} with the experimental retention times allowed evaluation of the importance of the contribution of the relaxation time to the whole retention time of the particles undergoing the focusing mechanism. The knowledge of this contribution is necessary for correct, high-performance, and high-speed accomplishment of microthermal field-flow fractionation experiments as well as for rigorous quantitative treatment of the experimental data. A more general approach that also takes into account the contribution of the thermodynamic force F_{TD} and that is not limited to the particular experimental conditions considered in this work is under study and will be published later.

CONCLUSION

The optimization of the operational parameters of a high-speed, high-performance microthermal focusing field-flow fractionation unit was analyzed, and it has been found that the linear velocity of the carrier liquid should not exceed a certain limit in order to keep the time of the secondary relaxation within the range of experimental errors of the retention time. The theoretical model developed to calculate the duration of the secondary relaxation time was compared with the experiments carried out on two different length channels. It has been found that the contribution of the secondary relaxation time to the retention time of model polystyrene latex can be neglected up to an average linear velocity of the carrier liquid of the order 0.4 cm/s under the studied experimental conditions. Above this limit, the relaxation time is important, and its impact on the performance of microfluidic separations should be taken into account.

REFERENCES

1. Di Carlo, D., D. Irmia, R. G. Tomkins, and M. Toner. 2007. Continuous inertial focusing, ordering, and separation of particles in microchannels. *Proc. Natl. Acad. Sci. U.S.A.* 104: 18892–18897.
2. Di Carlo, D., J. F. Edd, D. Irmia, R. G. Tomkins, and M. Toner. 2008. Equilibrium separation and filtration of particles using differeitial inertial focusing. *Anal. Chem.* 80: 2204–2211.
3. Di Carlo, D., J. F. Edd, K. J. Humphry, H. A. Stone, and M. Toner. 2009. Particle segregation and dynamics in confined flows. *Phys. Rev. Lett.* 102: 094503(4).
4. Janča, J., I. A. Ananieva, J. Sobota, and J. Dupák. 2008. Ultra-microthermal field-flow fractionation. *Int. J. Polym. Anal. Charact.* 13: 232–239.
5. Kašpárková, V., V. Halabalová, L. Šimek, J. Růžička, and J. Janča. 2007. Separation of bacteria in temperature gradient: Micro-thermal focusing field-flow fractionation. *J. Biochem. Biophys. Methods* 70: 685–687.
6. Janča, J. 2008. *Microthermal Field-Flow Fractionation: Analysis of Synthetic, Natural, and Biological Macromolecules and Particles*. New York: HNB Publishing.
7. Janča, J. 2006. Microthermal field-flow fractionation in the analysis of polymers and particles: A review. *Int. J. Polym. Anal. Charact.* 11: 57–70.

8. Segré, G., and A. Silberberg. 1961. Radial particle displacements in Poiseuille flow of suspensions. *Nature* 189: 209–210.
9. Segré, G., and A. Silberberg. 1962. Behavior of macroscopic rigid spheres in Poiseuille flow. 1. Determination of local concentration by statistical analysis of particle passages through crossed light beams. *J. Fluid Mech.* 14: 115–135.
10. Segré, G., and A. Silberberg. 1962. Behavior of macroscopic rigid spheres in Poiseuille flow. 2. Experimental results and interpretation. *J. Fluid Mech.* 14: 136–157.
11. Landau, L. D., and E. M. Lifshitz. 1986. *Hydrodynamics*. Moscow: Nauka.
12. Sutera, S. P., and R. Skalak. 1993. The history of Poiseuille law. *Annu. Rev. Fluid. Mech.* 25: 1–19.
13. Janča, J., J. Stejskal, I. A. Ananieva, J.-F. Berneron, J. Gearing, and M. Minárik. 2006. On the retention mechanism of nanometer and micrometer size particles studied by microthermal field-flow fractionation: Thermal diffusion and secondary effects. In *Thermodiffusion: Basics and Applications*, eds. M. M. Bou-Ali and J. K. Platten. San Sebastian, Spain: Mondragon Unibertsitateko Zerbitzu Editoriala.
14. Janča, J., and J. Stejskal. 2009. On the retention mechanism and secondary effects in microthermal field-flow fractionation of particles. *J. Chromatogr. A* 1216: 9071–9080.
15. Janča, J., and J. Dupák. 2005. Elimination of edge effects in microthermal field-flow fractionation channel of low aspect ratio by splitting the carrier liquid flow into the main central stream and the thin stream layers at the side channel walls. *J. Chromatogr. A* 1068: 261–268.