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Anomalous diffusion in microchannel under magnetic field

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Abstract

We have performed experiments to characterize the diffusion of an aqueous ferrofluid in water submitted to a magnetic field. Experiments were carried out in a microfluidic device to take advantage of the low Reynolds number flow conditions at the microscale. We have measured the concentration profile across the microchannel, which defines a characteristic length of the diffusion zone. This characteristic length varies as the square-root of the distance from the entrance of the channel divided by the mean velocity, which evidences a diffusive regime. However the application of a magnetic field is shown to inhibit the diffusion, with an increasing efficiency as the field intensity increases. We propose an explanation of this effect based on the anisotropy of the diffusion coefficient due to the magnetic field. This hypothesis is corroborated by numerical simulations.

Keywords: ferrofluid ; magnetic liquids ; anomalous diffusion ; microfluidic

1. Introduction

Microfluidic devices offer numerous perspectives in the domain of biochemistry, for example as a diagnostic device. Typically two liquids containing respectively an analyte and an indicator are flowing side by side in a microchannel. Because of the low Reynolds number in microfluidic systems, the flow is laminar and the transport of the analyte is only due to a diffusive process.

Microfluidic geometry offers a first-class tool to investigate diffusive effects in well-controlled conditions. As the flow is laminar, the diffusion front between two liquids depends only on the competition between the flow and the diffusion effects. Y-shaped (see fig.1a) and T-shaped microchannels are typical geometries for such experimental studies: the two liquids are injected separately, put in contact when the two inlet channels meet, and then flow side by side. The distance covered from the entrance is directly proportional to the so-called residence time, i.e. the length of time during which the two liquids are in contact. Here we have investigated the diffusion of a magnetic fluid in such geometry, and observed how the diffusion is modified when a magnetic field is applied.

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2. Materials and Methods

The ferrofluid was chemically synthesized through the Massart's method in the laboratory PECSA (UMR 7195 CNRS, University Paris VI, France). It is an aqueous solution of maghemite particles (γ-Fe_2O_3) of diameter 7.6 nm. Their volumic fraction is 10.45 %. In order to ensure their stability, citrate molecules are adsorbed at the surface of the nanoparticles (free citrate concentration = 3.10^{-2} mol/l). The other (miscible) fluid is a solution of water and glycerol having the same viscosity as the ferrofluid (2.8 mPa.s) in order to avoid any hydrodynamic instability.

The ferrofluid and the water-glycerol mixture are simultaneously injected with the same flow rate Q inside the Y-shaped microchannel (see fig.1a). The dimensions of the microchannel (whose fabrication is described in ref.[1]) are about 300 µm width (x-dimension) and 100 µm high (y-dimension). The microchannel is placed in the center of a magnetic coil which creates a homogeneous magnetic field along the y-dimension. The flow in the channel is visualized with a video camera mounted on a microscope.

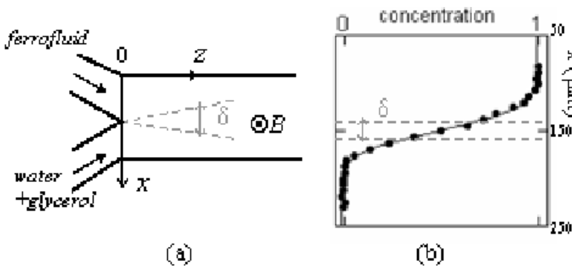

Fig. 1: (a) sketch of the Y-shaped microchannel. The diffusion zone gets larger as the flow proceeds along the channel. (b) Concentration profile across the microchannel. The circles are experimental data obtained at Q = 20 µl/min. The solid line is a fit determining the characteristic length δ (see text).

3. Experimental results

3.1. Diffusion without magnetic field

In order to characterize the diffusion front, we have plotted the light intensity profile $I(x,z)$ along the x-dimension using image analysis. To account for the non-uniformity of the light source, each image was divided by a reference image taken while the device was only flooded with water. The intensity I is linked to the ferrofluid concentration c by the Beer-Lambert law : $I(x,z) = I_0 \exp[-\kappa\, c(x,z)]$, where κ is a constant depending both on the light absorption coefficient of the ferrofluid and on the thickness of fluid the light passes through. Using this relation we obtain the concentration profile across the channel (see fig. 1b).

Following the theory of diffusion of a concentration step in an infinite medium [2], we have fitted the concentration profiles by the following expression:

$$c(x) = erf\left(\frac{x}{\delta}\right) \quad \text{with} \quad erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x exp(-v^2)\,dv$$

Here δ is a characteristic length of diffusion. This characteristic length has been determined for different flow rates (or mean velocity U), and different distances z (the entrance of the Y-shaped microchannel is set to $z = 0$, see fig. 1a). We have observed that δ varies as $(z/U)^{1/2}$. This is consistent with the diffusion theory which predicts that the characteristic length is equal to $(Dt)^{1/2}$, D being the diffusion coefficient of the nanoparticles in water, and t the residence time. Here the flow is laminar (Re ~ 0.03-1) and the residence time is equal to z/U.

Fig. 2: Sharpening of the diffusion front upon application of the magnetic field. The flow rate is $Q = 5$ µl/min. (a) No magnetic field. (b) A homogeneous magnetic field of magnitude 3.5 mT is applied.

3.2. Anomalous diffusion with a magnetic field

When an electric current circulates through the magnetic coil, the microchannel is submitted to a homogeneous magnetic field. For flow rates from a few µl/min up to about 50 µl/min, this leads to a sharpening of the diffusion front (see figure 2). On figure 3a we have plotted the characteristic length δ as a function of distance z: δ does not vary as the square root of z anymore. This means that the diffusion front between the water solution and the ferrofluid does not follow a diffusive law. In order to characterize it, we have fitted our experimental data with a power law: $\delta \propto (z/U)^{\alpha}$. This exponent α equals 0.5 when the magnetic field is off, and then decreases when the magnetic field intensity increases (see fig. 3b).

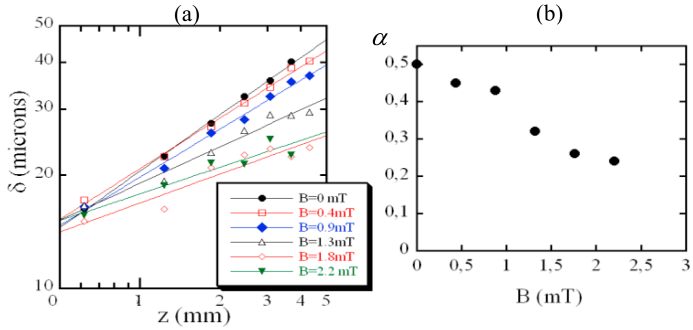

Fig. 3 (a) Log-log plot of the characteristic length δ vs. the distance downstream z, for different values of the magnetic field. (b) Exponent α as a function of the intensity of the magnetic field.

4. Discussion

In Sec.3 we have described how the concentration profile was deduced from the light intensity which is integrated in the y-direction. Actually, we have found that the length δ, characteristic of the size of the diffusion zone, is smaller than the height of the channel. Consequently the diffusive effects are not strong enough to prevent the non-uniformity of the concentration in the y-dimension because of the walls.

Previous theoretical and experimental works have described the so-called "butterfly effect" [3]. Due to the nonuniform velocity profile along the y-dimension, the residence times are larger near the walls (where the velocity is small) than in the center of the channel (where the velocity is maximum). The diffusion zone is then larger near the walls than in the center, causing the concentration profile to get the shape (in the xy plane) of a butterfly. Consequently non-negligible concen-tration gradients may exist near the walls, inducing diffusion currents also in the vertical y-direction.

When the magnetic field is switched on along the y-direction, the ferrofluid may develop an anisotropy in the diffusion coefficient. As shown by different works (see ref.[4]), the diffusion coefficient $D_{\perp}$ in the plane perpendicular to the direction of the magnetic field (i.e. in the xz plane) decreases, whereas the diffusion coefficient $D_{//}$ in the direction of the magnetic field increases. Finally the modification of the diffusion zone under the effect of the magnetic field could be explained as follows: whereas the transverse diffusion is inhibited, the vertical diffusion is increased, thus leading to the sharpening of the diffusion zone caused by the disappearance of the butterfly shape.

We have performed numerical simulations using the software Comsol in order to test this hypothesis. The Navier-Stokes equation and the convection-diffusion equation are solved in our 3D geometry. In order to describe the effect of the magnetic field, we have included in the equations an anisotropic diffusion coefficient. Following a microscopic model describing the effect of the magnetic field on the diffusion of a ferrofluid [4], we have introduced the two diffusion coefficients: $D_{\perp} = D - 1/3\ \Delta$ and $D_{//} = D + 2/3\ \Delta$. The numerical value for Δ is an increasing function of the magnetic field. Following experimental results from ref.[4], we have imposed $\Delta = D/10$ for a magnetic field $B = 2.6$ mT. In that case, the simulations predict that the anisotropy of the diffusion coefficients leads to the progressive disappearance of the butterfly effect. Moreover, an obvious sharpening of the diffusion front is observed, as can be seen on fig. 4.

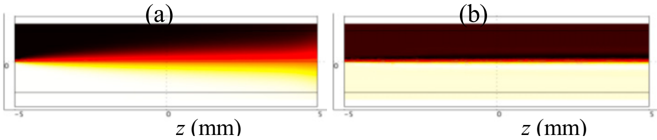

Fig.4: Numerical simulation of the diffusion zone with the channel geometry of fig.1a (a) The magnetic field is off. (b) With the magnetic field B = 2.6 mT.

5. Conclusion

We have observed that the diffusion of an aqueous ferrofluid in water may be inhibited when a magnetic field is applied. The system does not exhibit a diffusive regime anymore, the characteristic length of diffusion varying along the flow as z^{α} with $\alpha < 0.5$. Moreover the exponent α decreases from 0.5 for a zero magnetic field to value about 0.2 for $B = 2.5$ mT.

Our hypothesis, reinforced by numerical simulations, is that this effect is a consequence of the anisotropy of diffusion under magnetic field. In the absence of a magnetic field, the concentration is not uniform along the height of the channel. Under the effect of a magnetic field, the perpendicular diffusion coefficient $D_{\perp}$ decreases, whereas the parallel diffusion coefficient $D_{//}$ increases, leading to the disappearance of the non-uniformity along the height of the channel.

References

[1] C. Derec, C. Wilhelm, J. Servais and J.-C. Bacri, *Microfluid. Nanofluid.* 8, 123 (2010)
[2] L.D. Landau and E.M. Lifshitz, *Fluid Mechanics, Course on theoretical Physics* vol.6, Pergamon Press, London (1959)
[3] R.F. Ismagilov, A.D. Stroock, P.J.A. Kenis, G. Whitesides and H.A. Stone, *Appl.Phys.Lett.* 76, 2376 (2000)
[4] P. Ilg, *Phys.Rev.E* 71, 051407 (2005) and J.-C.Bacri et al., *Phys.Rev.E* 52, 3936 (1995)