MAGNETIC PARTICLES AGGREGATION IN THE PRESENCE OF A HYDRODYNAMIC SHEAR

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Summary *We present an experimental study of the aggregation of paramagnetic particles, carried out in the presence of a controlled laminar shear. Particles advected by the flow and suddenly immersed in a magnetic field are found to spontaneously form chains. Their lengths have proven to increase linearly with time, with a growth rate increasing as a power function of the shear. Observations agree well with a theoretical model based on a Smoluchowsky approach.*

INTRODUCTION

Most of the patterns produced in natural or industrial situations – fingers, dendrites, fractals – result from aggregation processes. The importance and ubiquity of these phenomena has motivated, over the last ten years, the implementation of well controlled experiments carried out in laboratories, using dielectric and magnetic particles. This effort led to confirm the relevance of the Smoluchowsky theory for these systems, a conclusion obtained for fluids at rest, i.e for diffusive situations. In natural systems however, the fluid in which aggregation takes place is most often moving, and it is known that, by bringing particles close to each other more rapidly than brownian motion, shear flows may considerably speed up clustering phenomena. The issue is thus raised as to know to which extent the piece of knowledge obtained in purely diffusive situations may be used when aggregation develops in the presence of a flow. The goal of the present work is to make a step forward in this direction, by performing controlled experiments in microfluidic systems.

DESCRIPTION OF THE EXPERIMENT

We use microchannels moulded in PDMS, or etched in glass and covered with a silicon wafer. Channel dimensions are 20 μm deep, 200 μm wide and 20 mm long. We investigate flowrates ranging between 5 and 50 nL/min. The superparamagnetic particles are 0.83 μm in diameter, encapsulating Fe_3O_4 microdomains (Bang Laboratories). The bead concentration used throughout the experiments varies between 4 and 10 μg/ml.
A magnetic field is created with a pair of Samarium Cobalt magnets, 0.3 T of maximum intensity, as presented in Fig.1. Magnetic fied lines are parallel to the flow. The experimental protocol consists first in imposing the flow without the magnetic field, and then, at time t=0, rapidly bring the magnets close to the channel. We further follow the temporal evolution of the system. In the experiment, the particles are vizualized by using dark field microscopy, using a LEICA inverted microscope, with an X10 objective. The image is further processed, using software NIH-IMAGE with private macros. The program allows to determine the mean chain length L(t), along with the corresponding number N(t) of isolated particles carried by the flow.

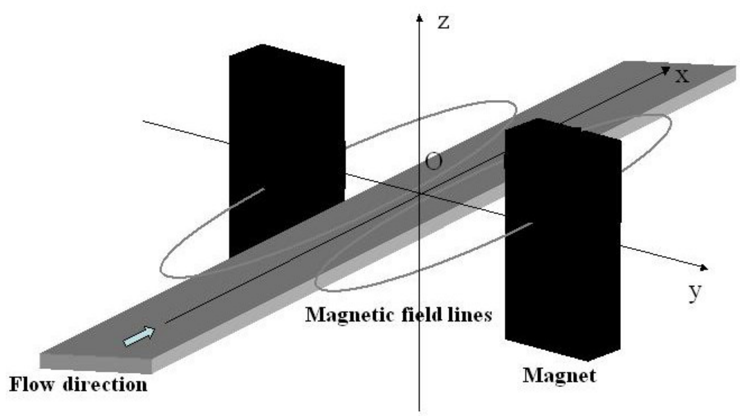

Figure 1: Schematic view of the experimental setup, represeting the pair of magnets, the micro-channel and a sketch of the magnetic field lines.

QUALITATIVE ASPECTS OF THE AGGREGATION PROCESS

We observe that the mechanism involved in chain formation most frequently involves particle-chain interaction : one chain and one particle located on two nearby streamlines, and therefore moving at different velocities, unavoidably approach each other and thus have the opportunity to aggregate, as illustrated in Fig2.

This process essentially takes place in the bulk, within fluid layers located close to the walls, where the shear is close to its maximum.

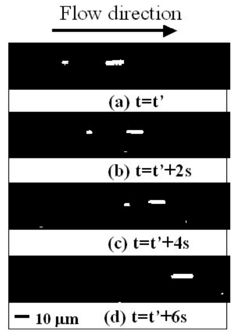

Figure 2 : Sequence of images showing the capture process. The flow goes from left to right at 40 nl/min. The magnetic field is longitudinal, with respect to the flow. The first images shows one particle appoaching a chain; some time later both have agregated.

RESULTS AND DISCUSSION

Fig 3a. represents the evolution of the average chain length L(t), for two different flow-rates, in a range of time comprised between 0 and 200 s. One sees that L(t) increases linearly with time, with slopes β depending on the flow-rate. Fig 3b. shows the evolution of the growth rate β with the shear rate S, estimated near the walls – where most of the chains lie.

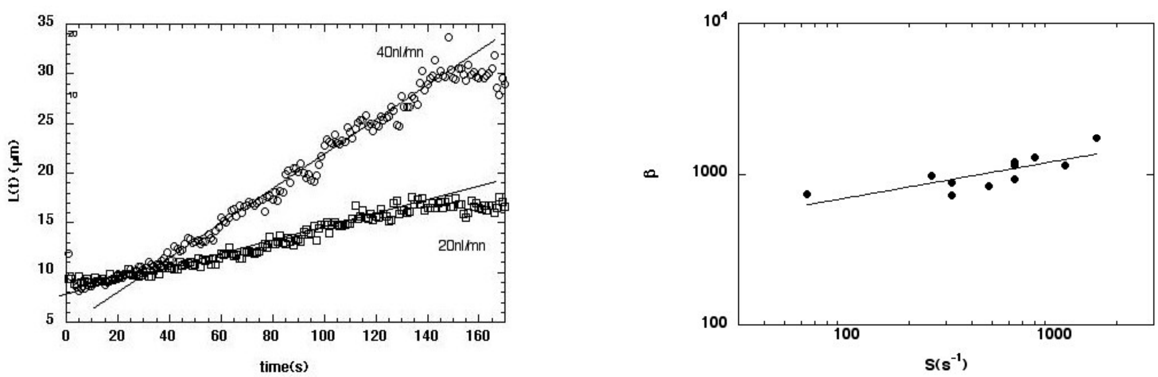

Figure 3 : a) Temporal evolution of the mean chain length for two different flow rates, 20 nl/min (squares) and 40 nl/min (circles) b) Evolution of the growth rate β with the shear in a log-log plot. One obtains the following power law as fitting the data : $\beta = 220.S^{0.25\pm0.1}$.

We further propose a theoretical model based on the analysis of the competition between the viscous forces and magnetic forces acting on a system particle-chain. We determine a radius of capture, within which particles coming from infnity aggregate onto a preexisting chain while the others escape. In this approach, one can show that the mean chain length increases linearly with time, with a slope proportional to the local shear raised to the power 1/4. The experimental observations made here are in good agreement with these expectations.

CONCLUSIONS

In conclusion, this work analyzes the aggregation process leading to the formation of chains, in the presence of shear flow, in micro-channels . We described the chain formation process, both theoretically and experimentally. The main observation is that the presence of the shear, coupled to the fact that the system is open, favors particle-chain interaction rather than chain-chain interactions, as in "ordinary" aggregation processes. As a result, the growth is linear in time. We found that, as a whole, theory explains the experiment quite satisfactorily. In these systems, miniaturization allows to produce substantial shears, while keeping the flows laminar.

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