Doctoral project : Hydrodynamic of acive fluids

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Because of their applications in a large number of fields such as biology, medicine, ecology or environmental engineering, the physics of active fluids (i.e. fluids containing particles moving autonomously) has been for some years the subject of intense research. In this family of fluids, we shall find suspensions of microscopic biological particles such as bacteria, algae, or microtubules. These fluids have many unique properties: such as the emergence of a collective movement[1] (bio turbulence), superfluid behaviors[2], and the appearance of spontaneous directional flows[3].

Despite all the efforts made, there is currently no theoretical framework modeling the hydrodynamics of these fluids. The main difficulty lies in the multi-physical coupling of parameters and the existence of coupling between scales (demonstrated for example by collective movements).

The aim of the doctoral project is to explore this new hydrodynamics by performing model flow experiments and comparing them with coupled flow and transport modeling. In the context of the thesis, we will focus on the displacement of a viscous fluid by an active fluid. This situation is found in a large number of situations such as oil recovery and has been studied in great details in the past years. It is known that the stability of the front between the two fluids depends on the contrast in viscosity between the two fluids. A stable front between the two fluids is obtained when the more viscous fluid pushes the less viscous fluid whereas an instability showing digitations will be observed if the fluids are inverted. It is by taking advantage of experimental models using flows in simple geometries such as those obtained between two parallel plates that theoretical models have been successfully developed. The main idea of the project is to follow the same approach to understand the physics of the displacement of an active fluid by a viscous fluid.

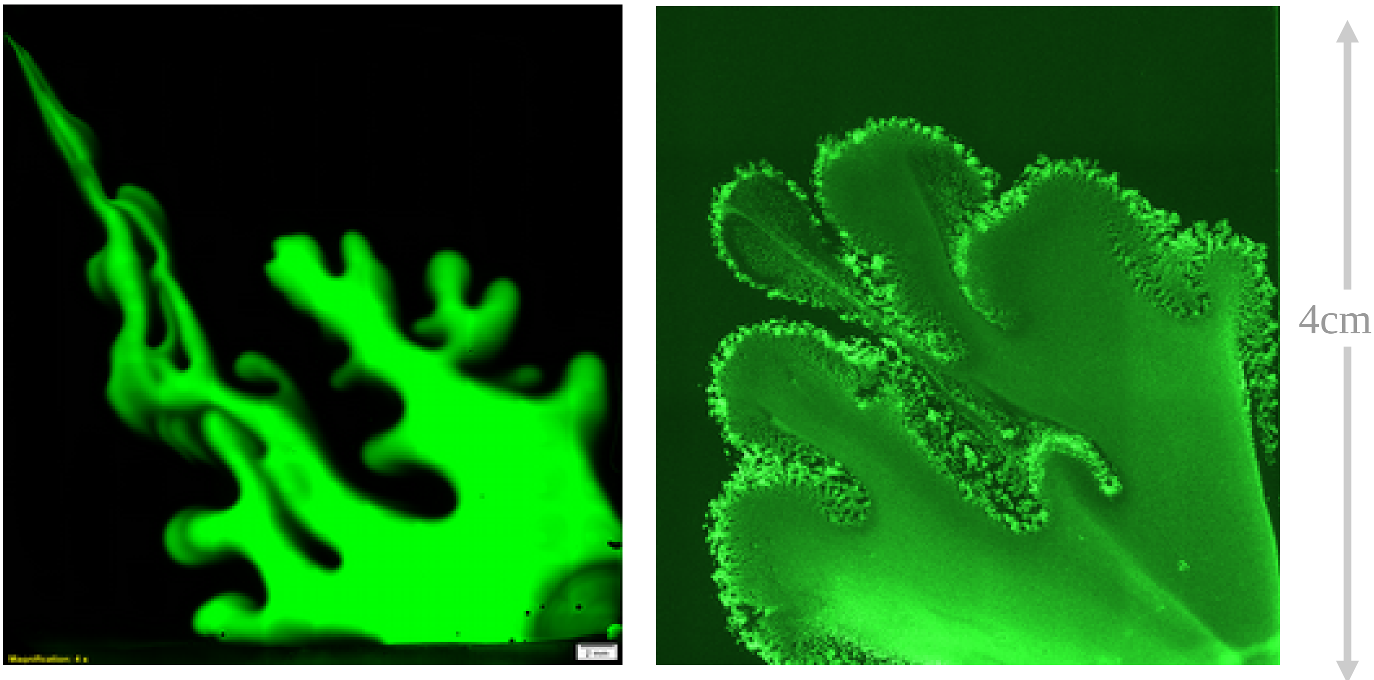
This project is part of the natural continuity of a MISTI project (MIT International Science and Technology Initiatives) between the French team and the US team involved in the doctoral project. Since the beginning of the project we have designed active fluids obtained from culture of fluorescent bacteria placed in suspension in a fluid of controlled viscosity. With this process, we can obtain very concentrated suspensions and thus control the activity of the fluid and observe the formation of collective movements. We have also developed a cell to perform the flow and observe the movement between the two fluids. The attached document gives technical details on the developed device and shows our first observations. It also gives details of the concepts of the model that will be developed.

In the example given below, it is clear that the presence of bacteria modifies the viscous instabilities. Over the period of the doctoral contract, we would like to carry out a complete set of experiments to model this new instability. In a first step, we will characterize the hydrodynamic mixture using fluids of the same viscosity but whose flow causes mixing between the two fluids. Since the activity is a function of bacterial concentration, the concentration gradient in bacteria will correspond to a gradient of activity. As we can see in the figure showing the displacement fronts (see appendix), the bacterial concentration does not vary continuously when crossing the front separating the two fluids. This first step will be important to determine the importance of nonlinearities on the transport and make a first modeling. The flows with viscosity contrasts will then be studied and we will adopt the same back-and-forth strategy between experience (in France) and modeling (in the USA).

[1] Concentration Dependence of the Collective Dynamics of Swimming Bacteria, Sokolov, A., Aranson, I.S., Kessler, J.O., Goldstein, R.E.,
Phys. Rev. Lett. 98 (2007).
[2] Turning Bacteria Suspensions into Superfluids, H. M. Lopez, J. Gachelin, C. Douarche, H. Auradou, E. Clement , Phys. Rev. Lett. 115,
028301 (2015)
[3] Transition from turbulent to coherent flows in confined three-dimensional active fluids, Sciences, Vol 355, Issue 6331 (2017)

Preliminary experimental results :

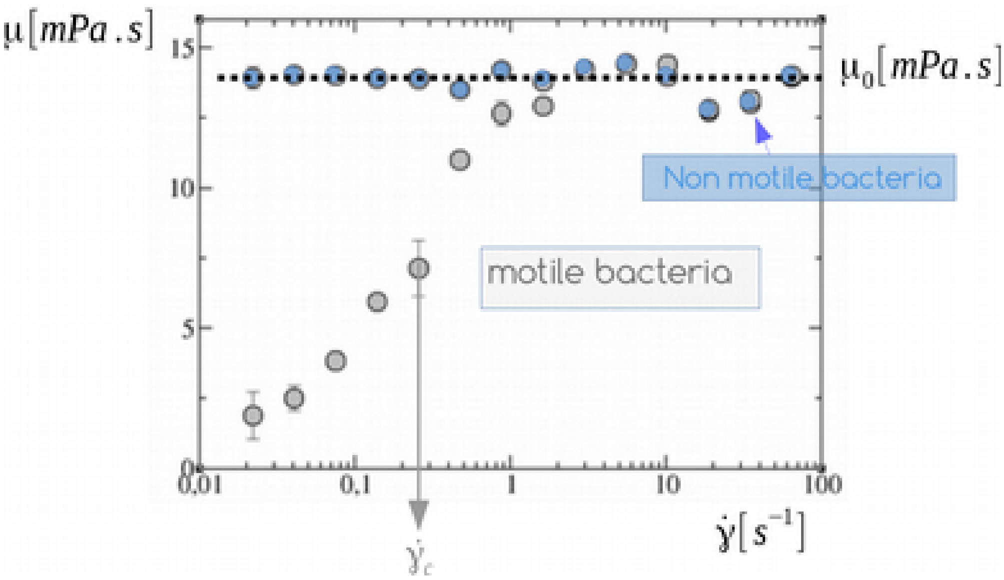
A) Two phase flow experiments :



Without Bacteria — With Bacteria

The images are visualisation done under a microscope (x40) of two flow experiments done at the same flow rate (Q=1µL/min). Here, a less viscous fluid (in grey or white) displaces a more viscous fluid (in black). The viscosity contrast is M=30 and the displacement front displays fingers. When bacteria are added in the fluids (right picture), the number of fingers is reduced.

B) Rheology of the active fluid:



Viscosity vs shear rate (rheogram) measured in a low shear rheometer. For shear rates below $1s^{-1}$, the viscosity of the active fluid decreases and is lower than the viscosity of the same fluid but containing no bacteria. In this experiments the bacteria are swimming in a solution containing 3% per weight of PVP360k allowing a good control of the viscosity of the fluids used. We will take advantage of this procedure to make experiments with controled viscous contrasts. The data were obtained with a bacterial concentration of 7.10^9bac/mL. More bacteria results in a lower viscosity at low shear.

C) Modelling of the two phase flow of active fluids:

We propose to model the displacement of one fluid by another (miscible) fluid in the presence of bacterial suspensions, in which the bacteria are motile and can lead to a reduction in fluid viscosity. The model system is a Hele-Shaw cell, where we can assume a Darcy-flow formulation in a quasi-2D system. The basic equations are a mass conservation equation for the fluid (assumed incompressible):

$$\nabla \cdot \underline{u} = 0$$

Where u is the fluid velocity, given by Darcy's law:

$$\underline{u} = -\frac{k}{\eta}\nabla p$$

Where **k** is the effective permeability of the Hele-Shaw cell, **p** is the fluid pressure, and **η** is fluid dynamic viscosity. The key aspect of this work is recognizing that the fluid viscosity is not a constant but, rather, a function of three variables:

$$\eta = \eta(\dot{\gamma}; x, c)$$

Here, $\dot{\gamma}$ is the shear strain rate, χ is the mass fraction of active-suspension-fluid, and **c** is the bacterial concentration. Our proposed detailed program of rheological measurements (see B) provide the basis fr finding novel functional forms for the dependence of the fluid viscosity.

The complete set of partial differential equations then include two transport equations; one for the fluid mass fraction and one for the bacterial concentration:

$$\frac{\partial \chi}{\partial t} + \nabla \cdot \underline{F}_\chi = 0 \quad , \quad \underline{F}_\chi = \underline{u}\chi - D_\chi \nabla \chi$$

$$\frac{\partial c}{\partial t} + \nabla \cdot \underline{F}_c = 0 \quad , \quad \underline{F}_c = \underline{u}c - D_c \nabla c$$

Where the key aspect is recognizing that the effective diffusion coefficient of bacteria, **Dc**, is a strong function of bacteria swimming speed and, therefore, fluid viscosity:

$$D_c = D_c(\eta)$$

Solving this set of 3 PDEs for pressure, fluid mass fraction and bacterial concentration would allow us to test quantitative hypothesis related to the interplay between viscous fingering and the evolution of motile bacterial populations.